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ICE-WORN ROCKS IN THE GORGE OF THE AAR BELOW THE GRIMSEL HOSPICE. (*From a photograph by J. Eccles, Esq., F.G.S.*)

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THE INTERNATIONAL SCIENTIFIC SERIES

ICE-WORK

PRESENT AND PAST

BY

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PREFACE

THOUGH separate papers, and even comprehensive books, upon ice and its work are numerous in our mother-tongue, to say nothing of other languages, a difficulty, to judge from my own experience, often attends the student. They seem to be written, in most cases, more with a view to advocating some particular interpretation of the facts than of describing the facts themselves. As regards these, it appears not seldom to be tacitly assumed that they must have some particular significance, from which it follows, as an almost inevitable result, that the hypothesis of one writer becomes the theory of his successors. Accordingly, I have endeavoured in the following pages to give greater prominence to those facts of glacial geology on which all inferences must be founded. For instance, a clay containing erratics consists of certain materials, has a certain structure, and stands in certain relations to other deposits. These are facts, and their bearing on the question of its origin—whether it be the ground-moraine of an

ice-sheet or such a deposit as is now accumulating on the Great Bank of Newfoundland—must be determined by the teaching of other facts, namely, by what can be learnt from regions the history of which is practically beyond doubt.

With this end in view, I have begun by giving a sketch of some such regions, and then have passed on to describe the phenomena which are the subject of more dispute. Here, in order to avoid the risk of misunderstanding the words of others, I have selected, as far as possible, cases which I have personally examined; these, however, so far as I have been able to ascertain from the literature of Glacial Geology, are fair samples of the whole series. To the descriptions—necessarily rather brief—I have appended a short statement of the interpretations which have been proposed, and have pointed out where they appear to me strong and where weak. In other words, I have endeavoured to follow the example of a judge rather than of an advocate; that is, to sum up the evidence on each side of a case, and leave the verdict to the jury. Like any such official, I have my own view as to what that verdict should be, and this doubtless will be disclosed to those who can read between the lines, but I may claim that it has not been formed hastily or without

experience. I saw a glacier for the first time in 1856; my earlier geological papers dealt mainly with ice and its work, and though for nearly twenty years I have written mostly on petrological subjects, I have never obeyed the well-known dictum and wholly cast off the old love.

In the later part of the book a method is indicated by which, I believe, we can approximate to the temperature at various localities during the Glacial Epoch, and the different explanations of this widespread refrigeration are stated and briefly discussed. To account for it, seems to me, in the present state of our knowledge, the most perplexing of all the problems which this Epoch presents.

Glacial geology is a large subject: the volumes of this series are comparatively small. Hence, in order to keep the present one within the prescribed limits, it has been necessary to pass rapidly over some points of considerable interest, and to omit others which have a less direct connection with an ice age. For instance, nothing is said of the coarse gravels on some upland plateaux and in certain river valleys, though many of them almost undoubtedly were formed when the climate was distinctly colder than it is at the present time, and some probably fall within the Glacial Epoch. But as their connection with ice is

less obvious and the Glacial Epoch did not begin with a particular year, I have dealt only with those deposits to which it can lay an undisputed claim. For the same reason nothing has been said either as to the physics of ice or as to the relation of Man to the Glacial Epoch; each of these topics having already formed the subject of a volume in this series.

A few of the illustrations are from my own rough sketches. For the photograph of the ice-worn rocks near the Grimsel I am indebted to my friend, Mr. J. Eccles, who took it when we were travelling together in Switzerland. I have also to thank other friends for kind help, among them Dr. Du Riche Preller for aiding me in examining the deposits near Zurich, the Rev. E. Hill for co-operation in visiting those of Eastern England, and Miss C. A. Raisin for reading the first proofs of this book.

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PART I

EXISTING EVIDENCE

ICE-WORK, PRESENT AND PAST.

CHAPTER I

ALPINE GLACIERS, PRESENT AND PAST

AMONG the highest peaks of the Bernese Oberland is a great upland valley, almost a natural amphitheatre. It is a gathering-ground of glaciers. Four of these, larger and more definite than the rest, descend from snowy saddles, which are separated by grand peaks—masses of steep ice broken by precipices and seamed by outcropping ridges of dark rock. The white floor of the valley, at this meeting-place of the frozen waters, is comparatively level. It lies some two thousand feet below the snowy saddles, and above them the peaks tower up about as high again. Minor tributaries of frozen rivers issue from shallower recesses in the flanks of the peaks themselves: and through a single opening towards the south, as through a portal, the united ice-streams glide slowly forth, forming the Great Aletsch Glacier, the largest in the Alps. Such a hidden group of glaciers is far from rare in the great mountain chains. To speak of the

Alps alone, the basins of the Gorner and the Fee Glaciers present a certain resemblance to that which we have described; those of the Argentière and the Northern Miage are yet more like it; while the Mer de Glace, among the aiguilles of Mont Blanc, is the nearest rival of this "Place de la Concorde of Nature," as it has been not inappropriately termed. One of the most striking prospects of this courtyard of the ice-king's palace is obtained from the Concordia hut, a rude chalet at the base of a rocky spur, in which the night is passed before making the ascent of the Jungfrau and sundry other peaks. From beneath this spot for a considerable distance the wide field of *névé*[1] shelves so gently as to seem nearly a plain, and its surface is almost unbroken. It is only as the slope steepens, on approaching the base of the actual peaks or the foot of the curtain walls, that crevasses become frequent. Then the frozen snow, for here it can hardly be called ice, is riven into strange forms, and usually one chasm—named the *Bergschrund*—wider and more persistent than the rest, severs the snow and ice of the glacier basin from the snow and ice of the actual peaks. Above this rift the solidified water is motionless, for it is fast frozen to the rocks; below it the whole mass creeps slowly downwards towards the valley of the Rhone. The snow which

[1] The name applied to the material of the upper part of a glacier, where it is more nearly in the condition of frozen snow. The German term is *firn*.

falls on the steep slopes of the peaks soon shoots down in avalanches to augment the accumulation below, and a thick layer gathers annually all over the wide expanse of the basin, for at this elevation rain is not common. So the glacier is born, so it is nourished. I have described its birthplace, I have dwelt on its beginning in some little detail, because in the pages which follow it will be necessary more than once to call up before our minds a similar scene.

The ice, as has been said, is at first comparatively smooth and free from débris. Here and there, however, a solitary boulder forms a black spot on its pure surface, or a small scatter of them trails forth from the foot of some rocky spur which is more prominent and precipitous than its fellows. These boulders after a time become more frequent, till at last they begin to form a kind of selvage on the edge of the ice-stream. Obviously, as the valley which it descends becomes better defined and sinks deeper into the mountain mass, the crags and precipitous slopes on either hand rise higher and barer, and stones more often come thundering down from them or are swept along by avalanches of snow. Now and again a block, more headlong than the rest, closes its career by one vast leap which lands it out on the glacier some hundreds of feet away from the rocks; but the majority fall on or near the edge, so that on this a mound of boulders, large and small, together with grit and earth, gradually accumulates and is slowly

swept along as the icy mass crawls downwards.[1] This mound is called a moraine. By the confluence of separate glens two glaciers are joined into one. If moraines have already formed at their sides, those at adjacent edges are combined.[2] The solitary blocks also travel on with the ice. If they are flat in form, they become elevated on pedestals; for they act as parasols, and so the ice beneath them melts less rapidly than the exposed surface of the glacier. Sometimes they travel to the end of the ice-stream; but if small, they are more often engulfed in a crevasse, where we leave them for the present.

When the bed of a valley has a fairly uniform slope, the glacier descends in a comparatively unbroken flow, till it melts away under the increasing temperature and is transformed into a river. In this case the medial moraines are also continuous, and produce great mounds, almost comparable with railway embankments. It must not, however, be supposed that these consist entirely of débris. The ice beneath them, as in the case of the glacier-table, is protected from the rays of the sun, and forms at last an inner ridge or core, on which sometimes the outer cover lies in very unstable equilibrium. The Unter Aar Glacier, on which the general gradient is only about

[1] The Alpine glaciers advance on an average about a foot a day. Large glaciers move more quickly than small; from 20 to 40, and in one case 50 feet has been recorded for the great ice-streams of Greenland. See Prestwich, "Geology," Part II. chap. xxxiii.

[2] This is called a medial moraine, the others being called lateral.

6 in 100, affords a good example of these unbroken moraines. Commonly, however, the bed of the valley is more step-like, one or two steeper descents interrupting the uniformity of its slope. As the glacier passes over these, it is rent into a wilderness of icy crags sundered by yawning crevasses. In them much of the moraine is engulfed; part of the débris descends to the bottom of the glacier, part is arrested in the narrower fissures and becomes embedded in its mass. At the base of the icy cascade the chasms often close up again, and the glacier moves on as a comparatively smooth stream. But the moraine has now lost its bank-like form, its materials have been scattered. Some of the blocks which were swallowed up in the shallower fissures appear again, in some cases disclosed by the melting of the ice, in others possibly[1] extruded by an upward motion in the mass itself. Thus, as a rule, the moraine, before reaching the end of the glacier, has become spread out over the surface. Sometimes for a considerable distance the mass of scattered débris — grit, gravel, and boulders of all sizes — almost conceals the lower part of the ice-stream. The load at last is dropped at the end of the glacier, where it forms a bank called the terminal moraine. This bank is usually more or less a crescent in plan, the convexity pointing downward, in correspondence with the shape of the ice-stream; and if

[1] The possibility of this supposition will be discussed in a later chapter.

its end remain for long at the same spot, the moraine attains considerable dimensions. If, however, the glacier be slowly shrinking, the mound is replaced by a wide scatter of boulders and débris. The same is true of the lateral moraines. These also occasionally form large banks, resting partly on the slope of the valley, partly on the edge of the ice. Sometimes they too may be, as it were, stranded, and become features no less definite than the terminal moraine; sometimes their materials also may be scattered, owing to a steady shrinkage of the glacier on the sloping sides of the valley. The volume of the moraine is dependent on a variety of circumstances, but the nature of the rocks in the adjacent crags and the arrangement of their divisional surfaces are always important factors. For instance, the amount of moraine stuff on the glaciers descending the western valleys of the New Zealand Alps around Aorangi is comparatively small, while on those of the eastern side it is very large, covering the ice-streams for about a quarter of their whole length, and piled up in heaps or hillocks more than fifty feet high. The cause is this: the mountain range is largely composed of slabby slaty masses of stratified rock, which dip towards the west. On that side the valleys descend nearly along the slope of the beds; the cliffs are low, and débris does not roll far; while on the eastern face the rock structure lends itself to the formation of great precipices, from which masses

are continually dislodged, to fall as avalanches of stone on the ice beneath.

Solitary blocks—sometimes many cubic yards in volume—may be seen, as we have said, travelling down the glacier; as it retreats, such blocks are occasionally stranded, either on the sloping flanks of the valley, or on some prominent hummock of rock which previously had been concealed beneath the ice, like a reef beneath the surface of a swollen river.

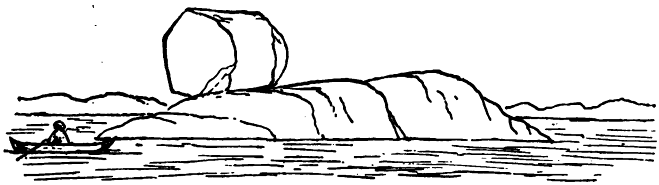


FIG. 1.—Perched Block on ice-worn rock islet, Nerlungshavn, near Langesund, Norway.

They lie sometimes on the bare rock, almost unaccompanied by moraine débris, and are poised occasionally in not very stable positions. These are called perched blocks. Most invaders set up monuments to commemorate their advance; the ice-king makes them memorials of his defeat.

But a glacier leaves other traces of its presence. If we had examined the bare rock near the Concordia hut, or the surfaces which, as we mounted the glacier, could be seen here and there shelving beneath the

margin of the ice, we should have noticed how much they differed in aspect from the crags in some dale of the limestone district of Derbyshire or among the granite hills of Auvergne. Instead of rough angular ridges, jutting knobs and rude hollows, we find rounded, smoothed, in places even polished surfaces. The last task, however, has been ill performed, for the smoothed face of the rock is scratched and striated—sometimes even rather deeply scored. This also is clearly the handiwork of the ice, and a little investigation will show how it is accomplished.

When a glacier moves over the rocky bed of a valley, the friction of so great a mass of ice must produce considerable effect. If it trespasses upon ground previously uncovered, it encounters rugged surfaces and jutting ledges. These it gradually wears away, making the rough places smooth, as angles are replaced by curves and craggy prominences by rounded knolls, in outline like the backs of sheep. From this resemblance such masses (of which we shall soon see more) are called *roches moutonnées*. (See *Frontispiece*.)

But it is not only the ice that abrades. The fragments broken off and the dust worn away from the underlying rocks are carried onwards and form an armature to the lower surface of the glacier. The moraine stuff, engulfed in crevasses which happen to extend from the top to the bottom of the glacier, also augments its rasping power. Moreover, when

the glacier makes its first advance, it may possibly sweep onwards loose material which has accumulated on the bed of the valley. This mixture of mud and stones, transported between the ice and the rock, is called ground moraine, or *moraine profonde*. As to its amount and importance there is much dispute, some holding that a very large quantity of materials travels in this way, while others think it to be comparatively small.

Boulders and grit, as already stated, are engulfed in crevasses, and in some cases ultimately become embedded in the ice like currants in a cake. Their amount obviously depends partly on the quantity of surface moraine, partly on the number and depth of the crevasses. A smooth glacier may be almost buried under débris and yet swallow up but little; while one which is rent by crevasses may have its moraines comparatively small, because it engulfs them almost wholly. So also the amount of moraine stuff which makes its way from the top to the bottom of a glacier in some cases may be insignificant, while in others it may become large. But débris, varying in size from fine mud to huge boulders, is transported in greater or less proportions in these three ways: on the ice, in the ice, and under the ice.

Streams, fed by snow-beds or by hanging glaciers, occasionally descend the slopes on either side and plunge beneath the ice, bearing with them much débris and many partially rounded stones, which go

to augment either the ground moraine or the material which is swept along the main channel of subglacial drainage. Boulders which travel under the ice and help in scoring the subjacent rocks must themselves suffer a like treatment. It is often "diamond cut diamond." The burnisher is burnished; the scratcher is scratched in its turn. So while rocks which have travelled on or in the ice remain remarkably angular, those that have been dragged beneath it are smooth and worn, on some sides rather than on others, according as they are more easily retained in the grip of the ice. This causes them to assume a peculiar subangular form, the broader surfaces being marked by striations, which not seldom are irregular in direction.

Yet one other mark is made by a glacier. Its surface is melted by the sun; the water trickles into rivulets, and the rivulets collect into streams, which quickly furrow a path for themselves; the ice is sculptured by a group of shallow channels like a model of a river basin on the land. But the course of the main stream of this drainage system is often cut short. If a crevasse opens across its path, the water plunges into the abyss and strikes on the rocks beneath. As the glacier advances, the friction of the falling water notches the ice in the opposite direction, so that the plunging action of the stream is limited to a comparatively small surface of the underlying rock; for if the ice travel forward more rapidly

than the stream can cut backward, a new chasm in all probability will open before long in the original position, and the cascade will begin to work afresh

FIG. 2.—Scratched stone from the till of Boston. Natural size about one foot and a half long by ten inches wide. (From photograph.)

over its former path.[1] Boulders and débris from time to time slip into the stream and are swept down

[1] These wells in the ice are called *moulins*.

the waterfall; they are hurled against the rock beneath, and whirled round and round before they are carried onward along the subglacial trench which the torrent has worn, so that at last a hollow begins to be formed. This, when once it can retain some of the fallen blocks, is quickly deepened. As in the bed of any mountain torrent, so here a pot-hole is ground out, but the peculiar mode of excavation usually makes the hollow beneath the glacier deeper in proportion to its breadth than in the other case. It is frequently several feet, occasionally some yards, in depth. During the retreat of the ice these hollows, called "giants' kettles," often become filled up with mud and stones.

Such, then, are the effects of a glacier: namely, perched blocks and moraines, terminal, lateral, and subglacial; *roches moutonnées;* and surfaces smoothed or polished and striated or channelled, pitted occasionally with giants' kettles. Where these occur, it may be inferred that a glacier formerly existed, even though at the present time the snow vanishes from every recess in the surrounding mountains long before the summer reaches its end. It must be remembered, of course, that rocks and stones may be worn or striated by other causes than the action of a glacier. A mound need not always be a moraine; a perched block may possibly be due to some other agency; but if due care be taken to avoid mistakes, the aforesaid marks indicate the path of a glacier as certainly

as our footprints on the sand show that some one has been walking on the sea-shore.

We must now proceed to examine the valleys below the ends of the glaciers. In such a mountain-chain as the Alps, the evidence, with many variations in detail owing to local circumstances, is everywhere substantially the same. Take, for instance, the valley of the Aar in the neighbourhood of the Grimsel hospice. The little tarn beneath the precipices of the Nägelisgrätli is surrounded by billowy hummocks of granitic rock, "like the backs of plunging dolphins." Far above the bed of the valley, up the steep crags leading to the "Dead Man's Lake," up the great mountain buttress round which the river bends sharply to the north, the rocks everywhere are rounded and smoothed and striated. (See *Frontispiece.*) All down the deep and narrow glen for some miles the story is the same: ice-worn, ice-scored rocks, perched blocks and scattered débris, prove that a vast glacier once welled up high against the precipitous slopes on either hand; for the marks extend almost from the present level of the stream to some two or three thousand feet above it, and further examination shows that many a lateral glen, in which now perhaps only a small snow-bed lingers in some sheltered corrie, once gave birth to a tributary glacier.

Another thing, however, is obvious; the dominant outlines of the valley are those indicative of the action of water, for it is V-shaped in section. It

has been filled with ice, it has been modified by ice, but it has been blocked out by running water and the ordinary atmospheric forces. No one accustomed to travel in non-glaciated as well as in glaciated regions can fail to decipher the familiar characters of ordinary rain and river action, though these are sometimes blurred by the palimpsest writing of the ice-scribe. Moreover, with one or two slight exceptions, as at the Räterichsboden, the V is always acutely pointed. This fact, and the general freshness of the ice-worn surfaces, suggest that no very long time, as geologists reckon, has elapsed since the ice melted from this part of the valley. Below the Handeck Falls, on approaching Guttannen, the Haslithal widens a little, and the distinctive outlines are to some extent obscured; but no level space of any importance is found until the confluence of the Gadmenthal with the main valley is reached. Here is a grassy basin, the flat meadows of which suggest that it formerly may have been a small lake, which has been filled up by débris brought down by the torrent. Beyond this little oasis in the wild mountain-land the valley is barred by a limestone ridge, called the Kirchet, through which the Aar has cut a narrow gorge.[1] The side which faces the east is steep, almost precipitous, but up and over this, some 300 feet above the valley, the glacier has been

[1] This cañon has been made accessible, and affords a wonderful study of the erosive action of a torrent.

forced by the resistless pressure of the accumulating mass behind. Rocks, everywhere ice-worn, and sprinkled with boulders from the upper parts of the valleys, place this fact beyond question. On the western side of the Kirchet lies the level delta of the Lake of Brienz, over the site of which, as will presently be seen, the great ice-stream formerly passed on to the lowlands in the same general direction as is taken by the present river. Every valley in the Alps affords similar testimony, though it is not always written in characters equally distinct. In some districts the rocks disintegrate more easily, the valleys are wider, their floor is buried beneath gravel and alluvium, their sloping sides are covered by débris which has been swept down from the upper crags by avalanches or streams or local "cloud-bursts." In one place ice-worn rocks such as have been described are conspicuous; in another, erratics strewn over zones on the mountain-sides, or some solitary perched block, or an isolated terminal moraine, bear testimony which is equally valid.

On the steep slope leading from the valley of the Rhone into the Val d'Illiez, erratics, formerly many hundreds, if not thousands, in number, are strewn among the vines and under the shadow of the Spanish chestnuts. They are mostly of crystalline rock, while the valley itself is wholly excavated in limestones and slates. They have been derived from various places higher up in the valley of the Rhone, one of

the commonest rocks being a protogine. This beyond all question has come from the aiguilles which rise above the Glacier du Trient at the eastern end of the Mont Blanc range. Generally these blocks are scattered over a zone varying from about 100 to 250 yards wide; occasionally three or four may be seen practically in contact. Numbers have been broken up for building, road-metalling, and wayside posts. The volume of the largest is estimated at 60,480 cubic feet, and on its flat top a pavilion has been built. Similar boulders—though generally not so large—may be traced along the shore of Lake Leman, even down to Geneva. Here and there may be found a peculiar mottled green and white rock, which has started on its journey from crags on the upper part of the Allalin Glacier in the Saasthal.[1] Erratic blocks, however, are not restricted to the neighbourhood of the Lake of Geneva; they are scattered over the lowland between the Alps and the Jura; they may be traced up the flanks of the latter mountains; on the Chasseron they reach an elevation of fully 3000 feet above the lowland, and from that their upper limit descends in either direction.[2] On the limestone slopes of the Jura above

[1] The rock is a variety of euphotide, chiefly consisting of a saussuritic mineral and smaragdite. It occurs *in situ* in no other part of the Alps.

[2] A number of important facts as to the distribution of these blocks will be found in Professor A. Favre's well-known work, *Recherches géologiques dans les Parties de la Savoie . . . voisines du Mont Blanc*, chap. vi.

Neuchâtel, many erratics are scattered among the pine-trees. The largest, the famous *Pierre à bot*, contains from 40,000 to 45,000 cubic feet, and is perched at a height of 820 feet above the Lake of Neuchâtel. It, like most of its neighbours, is protogine from the Mont Blanc range.

The Alpine and sub-Alpine region will repay us for further study, because there is no reason to suppose that any portion of it has been submerged beneath the sea, either at any time during the Glacial Epoch, or since this came to an end. Hence we may safely assume all the glacial deposits to be results of the action of land-ice, and regard them as types for comparison with those in other countries of which the origin is less certain. Accordingly we will retrace our steps to the ends of the glaciers, in order to ascertain what difference, if any, exists between the morainic material which is still in process of accumulation, and that which has been distributed over the lowlands. In the recent moraines blocks of various sizes, from a few inches to many cubic yards in volume, are confusedly piled together; the latter, however, are comparatively rare, though occasionally a monster, like those already mentioned, may be found; as, for instance, the great block of impure serpentine lying some distance from the end of the Schwarzberg glacier on the little plain near the Mattmark Hotel, which measures about 50 feet each way. A quantity of mud, sand, and small stones is

mingled with the coarser materials in the moraines. In those at the foot of the Fee Glacier, the fine material appears generally to be at least equal in volume to, and sometimes rather more than, the larger blocks; in other cases it is not quite so much. We are not, however, obliged to suppose that all this mud has been extruded from beneath the glacier, for it is as abundant in the upper as in the lower part of the moraine, and the sloping surface of the ice is coated for a considerable distance up with mud and sand, so as to be a dull grey in colour. It is well known that fine mud, grit, and small stones are common on the surface of glaciers. This material is swept down from the barer cliffs of the mountains by snow avalanches or streams, or is formed during the fall of rocks as they impinge on the crags, to their mutual destruction. A cloud of dust accompanies the volley of descending fragments; for smokeless powder is not used in Nature's artillery. The comparative rarity of ice-worn and striated stones in the recent moraines is a further proof that they owe little to subglacial débris. The torrent, however, which issues from beneath the glacier and carries off the water—whether melted from its surface or contributed by streams which have made their way under the ice—is turbid with mud, much of which has been derived from the subjacent rocks. The amount varies with the time of the year, because the stream is small and clear, comparatively speaking,

in the winter months, for its volume largely depends upon the rate at which the ice is melting. Dolfuss calculated that the Aar in the summer time transported at its issue from the glacier 142 grammes of sediment per cubic metre, or $\frac{1}{7040}$ of the weight of the water, but that the amount for the whole year was only $\frac{1}{20000}$. Observations on seven Greenland and ten Norwegian glaciers gave as the mean results for the summer months 147.9 grammes per cubic metre; and Professor Helland calculates that all the glaciers of Justedal during the month of July transport 2,000,000 kilogrammes, and during the entire year 180,000,000 kilogrammes, which is equal to a mass of rock 41 metres cube. As the area of these glaciers is about 900 square kilometres, this mass is equivalent to the removal annually of a layer about .0766 millimetres thick (or .003 inch) from the entire surface beneath the ice.[1] But not even the whole of this, as already said, is really worn away from the glacier bed; for a not inconsiderable part either comes from the stones which help in the work, or has been washed by glacier streams from the surface of the ice, or has been swept beneath it as débris by lateral torrents. Professor Heim, as the result of his careful observations, considers glaciers, as a rule, to be much less important agents of denudation than mountain torrents, for one

[1] See summary of Heim's *Handbuch der Gletscherkunde*, by F. F. Tuckett. *Alpine Journal*, xii. p. 301.

of these, though its collecting basin is only one-tenth of the area of the Unter Aar Glacier, has been known to bring down, when swollen with rain, from 10,000 to 100,000 cubic metres of débris in the course of a day or two. Its ordinary daily yield is no doubt less than that of the glacier, but the occasions of energetic action are so frequent as to make the work of the one much more important than that of the other. Certainly the Alpine glacier at the present day transports but little ground moraine. Observers have succeeded in making their way for short distances beneath the ice, and have found between it and the rock nothing more than a mere film of mud, with an occasional boulder, generally small and solitary.

The mode in which a glacier terminates varies with local circumstances. Here it may end in a ravine, there descend on to comparatively level ground; here the final ice slope may be steep, there it may shelve down gently; here it may be completely masked by débris, and the white water spouts and foams from among the grey boulders as if from hidden springs; there, as is more usual, the torrent rushes out into the daylight from beneath an arched cavern of ice which vies in colour with the turquoise. Sometimes a bare and smoothed slope of rock must be climbed to reach the ice, but in the case of the larger glaciers a comparatively level space generally lies at its foot, the breadth of course being dependent

on that of the valley which it occupies. This is strewn with boulders and stones, some subangular, occasionally even rounded, some angular and uneven. The former have been brought by the torrent, or at any rate have performed much of their journey, beneath the ice; the latter have travelled for the whole way upon it. Similar narrow plains may often be observed in the upper parts of valleys, the heads of which are occupied by glaciers, as, for example, between Saas-im-grund and the Mattmark Hotel; but as the torrent is constantly adding débris to these deposits, especially in time of flood, it soon becomes difficult, except in the case of the largest erratics, to ascertain how much may be regarded as a direct, and how much as an indirect, result of the glacier,

Sometimes, however, these erratics furnish us with testimony which has a not unimportant bearing on the question of the effect of ice. The glaciers of the Alps, even at the present day, are liable to oscillations,[1] which occasionally are far from unimportant. About forty years since they began a general retreat, which, however, appears now to have ceased. In some cases a length of more than a thousand yards of rock or débris has been exposed, which previously had been concealed beneath the ice, and the thickness of the glacier has been diminished in places from 150 to more than 300 feet. Where the ice has rested on

[1] To these a fuller reference will be made in a later chapter.

a slope, bare rock has been disclosed, sprinkled here and there with a little débris, most of which had fallen from the retreating glacier. This, however, is what was seen in 1875 at the end of the Glacier des Bois. At that time it just reached the level bed of the Arve valley, and reclined on ice-worn rocks, with its end fitted into a sort of glen or ravine not more than about thirty yards across. "Below it there is a stony plain covered with the usual mixture of rounded and angular blocks. . . . Among these, a short distance from the end of the glacier, and rather near the left bank of the valley, is a huge block of protogine about 12 × 8 yards in area and 4 yards high. The top of this, and to some extent the sides also, are striated by ice moving in the direction of the present glacier. The Glacier of Argentière is in a nearly similar position; about the last fifty yards rests on the stony bed of the Arve valley, the remainder lies on rocky slopes. In front of it there is an extensive area, now covered with boulders, which, within the last few years, has been abandoned by the ice, and is enclosed by a comparatively fresh terminal moraine. Many of the smaller blocks on this area, now almost concealed by rubbish scattered from the retreating glacier, are smoothed and striated as if by passing ice; the general uniformity, however, of their upper surface is unfavourable to the idea of the glacier having any great power of 'churning up' the deposit beneath. Here and there are large prominent pro-

togine blocks, several of which distinctly show by the striations on their sides and surface that the glacier has flowed over them. Three lie near together; their tops are polished and striated, and littered over with moraine; they do not form part of a lateral or ordinary terminal moraine, but are in an open plain. Striations—*stoss* and *lee seite*—everything is just as it should be had the glacier flowed over them, and each has a 'tail' of moraine. The largest was about 12 × 7 × 5 yards."[1]

Three important conclusions follow from these observations: (1) That in glaciers of moderate size, such as those of the Alps, the amount of ground moraine is small, not only in comparison with that transported on the surface, but also absolutely; (2) That the ice, even under apparently favourable circumstances, though it may act as an *abrasive* agent, has practically no power to *excavate*; and (3) That its movements, whatever be the physical explanation, resemble those of an imperfect fluid.

In descending an Alpine valley from the foot of a glacier, we commonly fall in with some old moraines: often they are overgrown with trees, but occasionally the torrent keeps a fresh section exposed, and allows their structure to be examined. The materials resemble those of the moraines in the immediate neighbourhood of the ice, except that they are sometimes slightly more consolidated, and that the ratio of fine

[1] *Geological Magazine*, 1876 p. 198.

to coarse stuff seems to increase with the distance from the glacier. An old moraine on the right bank of the river, just below the confluence of the Vorder and the Hinter Rhine, will serve as an example.[1] A general idea of its structure may be obtained from the annexed sketch. Angular blocks, mostly of lime-

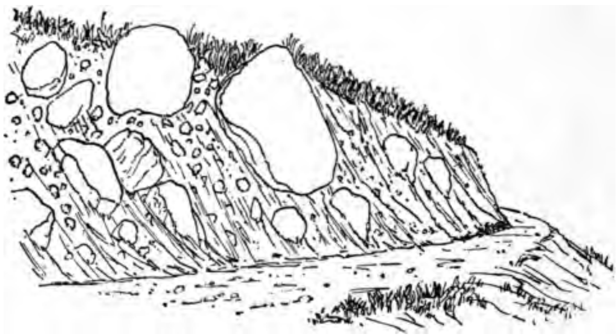


FIG. 3.—Section (diagrammatic) of an old Moraine, near Reichenau, Switzerland.

stone, varying in size from nearly 100 cubic feet downwards, together with a few, usually more rounded, of granitoid rock, are embedded in an earthy material full of fragments, which commonly range downwards from a cubic inch to one sixty-fourth of the same. This finer material, including the sandy clay, seems

[1] Fresh sections can be seen by the side of a little path which turns off from the highroad just before the bridge at the entrance to Reichenau from Chur.

to be about one-half of the whole mass, and in it not a trace of stratification could be detected.

From this moraine, which is a good instance of the débris left by the ice in the larger Alpine valleys—that is to say, by the glaciers at a time when they occupied numerous glens from which they have now disappeared, and when their trunk streams were some forty miles in length—we pass to examine the deposits on the lowlands. Those which occur in the neighbourhood of the Lake of Zurich may be taken as an example, for here we are on ground which is classic in the history of the work of ice. This region affords clear evidence that during the Ice Age the great glaciers advanced and retired, probably more than once. For the moment, however, we shall refrain from entering into the details of this question, and shall content ourselves with describing the nature and general relations of the associated deposits. The first, and by no means the least interesting example, is to be found on the Uetliberg, a rather long and narrow ridge, the summit of which, commanding a lovely view of mountains and lowland, is 1522 feet above the level of the lake. Its crest consists of a mass of gravel, which is sufficiently consolidated to form rather precipitous crags. This rock presents a superficial resemblance to the well-known *Nagelfluh*, a conglomerate of Middle Tertiary age; that, however, is so hard that, when it breaks, the included pebbles are split, while in this they tear out rather readily

from the matrix.[1] On the Uetliberg this gravel is full 50 feet thick. Very many of the pebbles are from 2 to 3 inches in diameter; occasionally they are larger and more subangular in form, now and then exceeding a foot. Sandy partings, from a few to perhaps a dozen inches in thickness, occur here and there, sometimes showing false bedding. The mass passes down into stratified sand, in which smaller pebbles occasionally form a seam, but generally are scattered sparsely. This finer material is seen to underlie the gravel for a depth of 6 to 8 feet, and beneath it comes a mass of earthy stuff, including boulders and stones, more or less rounded and sometimes striated; the volume of the finer material apparently exceeding that of the coarser. Large blocks seem to be not very common; some, however, are preserved in the hotel-garden, one being a mass from the true *Nagelfluh.* That this is a glacial deposit is as obvious as that the overlying mass is a river gravel. Further down the Limmat the "*Decken-schotter*" may be seen much nearer to the level of the river. On its left bank, near the old-fashioned town of Baden, is a prominent hill, noted for a picturesque ravine called the *Teufelskeller.* The pebble-bed apparently forms not only the crags at

[1] Hence the latter rock is called the *löcherige Nagelfluh,* or "pitted" *Nagelfluh,* to distinguish it from the former. Similar gravels occur in many other places along the northern outskirts of the Alps; and as they not unfrequently form "caps" to more perishable underlying beds, they have also been named *Deckenschotter.*

the top, but also no small part of the whole hill, so that its base, which rests on molasse,[1] can hardly be more than a couple of hundred feet above the stream. The materials vary from coarse to fine, and from subangular to fairly rounded, the smaller stones as a rule being the better worn. In the upper part of one section they run large, some of the blocks being about half a yard in diameter, while in the lower part the pebbles seldom exceed the size of a goose-egg, and are commonly less.

Many of the minor inequalities in the town of Zurich are really moraines, the origin of which is still betrayed by their form, notwithstanding the covering of houses. The Lindenhof, a low hill overlooking the Limmat, is one instance; the same is true of the Hohe Promenade, and of all the terrace on which the Polytechnic is built. Similar deposits may be traced on the Zurichberg.[2] Excavations in this locality are usually sufficiently numerous to give a good idea of the material. The matrix is a greyish earthy loam or clay, fairly stiff; the stones represent a great variety of rocks from the mountains about the glens of the Linth and Limmat, and they commonly run from about six inches in diameter downwards. Boulders a foot or two in length occur, but are far from common. They vary in form from sub-

[1] A sandstone about Middle Tertiary in age.

[2] These, however, are considered by Swiss geologists to belong to a different epoch of glaciation.

angular to sub-rotund; a few being quite angular, and a rather larger number well-rounded pebbles. The peculiar shapes suggestive of subglacial transport, and striations are by no means rare. Perhaps about three-fifths of the material would go through a riddle with meshes large enough to pass a small hazel-nut. The mass is not stratified, except perhaps in one or two places, where this structure seems to be very faintly indicated. In one opening the base of the mass was exposed. It was underlain by about five feet of clay, into which it passed rather abruptly. This was yellowish in the upper part, greyer and more sandy in the lower, and one or two dark streaks suggested the presence of carbonaceous matter. Below this clay was the usual molasse, its surface being rather rough and slightly broken.

On the hill above Thalwyl, on the left bank of the Lake of Zurich, is another group of excavations in a morainic deposit, which requires a brief description. The clayey matrix contains rather more sand than in the last-named instance, and fragments, from the size of a horse-bean downwards, are more numerous. Larger blocks also are commoner, some occasionally occurring which are four feet or more in diameter. These are usually angular, but those of smaller size, as a rule, are more or less worn, even rounded pebbles being not very rare. Stones smoothed and striated by ice action appear to be more abundant here than in the pits near Zurich. A general idea of the

appearance of the mass may be formed from the annexed rough sketch, though in it the smaller fragments are usually not indicated.

One other group of deposits still demands mention. Immediately below the older part of Zurich, after the confluence of the Sihl, the valley begins to widen.

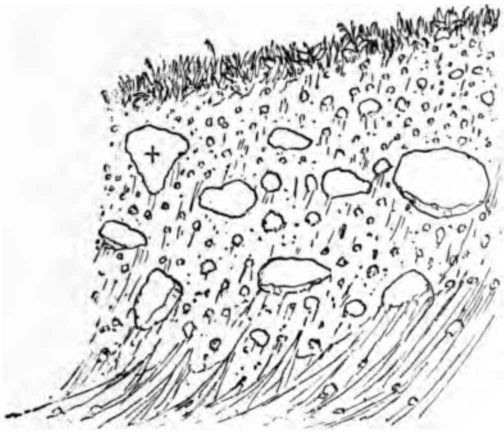


FIG. 4.—Section of Till, near Thalwyl, Lake of Zurich. + This block is about half a yard in diameter.

Its floor is a level plain several yards above the surface of the Limmat. Pits are common in which the material of this plain is exposed to a depth of seven or eight yards. It is a gravel, generally coarse, interstratified with occasional seams of sand, both often showing false bedding. The pebbles are more or less

water-worn, varying from subangular to well-rounded; not unfrequently they are three or four inches in diameter, or occasionally still larger, though seldom quite reaching a foot. The mass, in short, is a typical river-gravel, such as may be seen by the side of almost any of the great sub-Alpine rivers, rising in terraces sometimes to a height of eighty or a hundred feet above the present level of the water. It is, however, older than some of the morainic deposits, as is proved, for instance, by a section about ten miles below Zurich, near Killwangen, where excavations have been opened in a gently shelving slope near the railway station. In one of the pits, the lower part, some fourteen feet in thickness, consists of stratified gravel, like that near Zurich, though perhaps the pebbles are slightly more rounded. Over this comes about four feet of morainic material. In it erratics are numerous, but its earthy matrix, to a certain extent, is mixed up with gravel, the latter here and there retaining signs of stratification. This deposit is covered by soil containing pebbles and erratics, generally about a yard in thickness. An adjoining pit affords a similar section, but the moraine stuff, as is shown in the annexed diagram, roughly conforms to the slope of the ground. It is underlain, as in the other pit, by stratified gravel. The erratics are more or less angular, often from 15 to 18 inches, and occasionally even 3 feet in diameter, but a block of true *Nagelfluh* which was lying in

the excavation measured quite a couple of yards. Probably the morainic stuff was once much thicker, and has been reduced by sub-aërial if not by fluviatile denudation. The pressure of the ice, which seems here to have been forced for a short space up a slope, has apparently ploughed up a little of the underlying loose gravel and mixed it with morainic

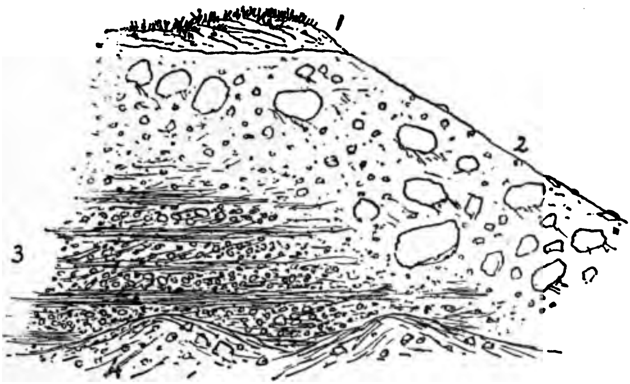


FIG. 5.—Till (2) resting on old gravel (3) of Limmat Valley, near Killwangen Station (diagrammatic). (1) Soil.

material of the usual character. The abundance, however, of angular blocks in the latter may be taken as an indication that it is by no means wholly composed of subglacial débris.

In the lowlands bordering the Alps ice-worn rocks are seldom seen. Gravels such as have been described cover large areas to a considerable elevation

above the present streams, and much of the surface is masked by accumulated débris; for the rock almost everywhere is a soft sandstone, which yields readily to the action of the weather. There is, however, one locality where the tool-marks of ice are singularly interesting and well preserved. This is the well-known "glacier garden" near the Lion monument at Lucerne. A narrow rather steep-sided valley, which opens out as it gradually descends towards the lake, forms a sort of connecting passage between it and the valley occupied by the Rothsee. In digging the foundation of a house, a short distance from the Lion monument, and a little above the bed of the valley, a fine instance of a "giant's kettle" was found, and further excavation led to the discovery of the group, which is now one of the sights of Lucerne. They are about nine in number, irregularly dispersed over an area of perhaps half an acre, the biggest being about 26 feet wide and 28 feet deep. The bed of more than one has assumed a spiral form, thus showing that the gyratory movement of the plunging water of the cascade was constant in direction. These "kettles," when first discovered, were filled with débris, and still contained the large rounded boulders by which they had been mainly excavated. The surface of the sandstone between the most conspicuous examples is smoothed and striated, but a shelving craglet or steep face of rough rock, which in one place interrupts the uniformity of this surface,

MAP OF
GLACIAL MOVEMENTS IN FRANCE AND SWITZERLAND.
COMPILED BY FALSAN.
Arrows indicate direction of motion.
Brest
Crozon
Strasbourg
Rhine
RHONE GLACIER
GLACIERS OF THE RHINE
Sion
MT. ISERAN
GENEVRE
MT. VISO
Nice
PIC D
Longitude
50
48
46
44

indicates that the action of the ice has not been continued long enough to obliterate all previous inequalities. The débris must have been deposited after the moulins had ceased to act, and in all probability during the retreat of the glacier. These "kettles" were found, unless appearances are misleading, within a very few feet of the surface, and the overlying material is not at all characteristically morainic; moreover, a rather careful search in all accessible places in the neighbourhood failed to show more than slight traces of any such deposit.

In short, at the time of the maximum extension of the ice-sheet, almost the whole of the Swiss lowland was buried, and the ice welled up against the flanks of the Jura to a height of 3000 feet above the Lake of Neuchâtel, whence it extended northward to the neighbourhood of Soleure. Along the present course of the Rhone it sent out a huge lobe far beyond the frontier of Switzerland, for erratics and other glacial deposits have been traced to within a few miles of Lyons. It is estimated that altogether the ancient glacier of the Rhone was not less than 270 miles in length.

The glaciers on the southern sides of the Alps were hardly less extensive than on the northern. They descended the valleys, they passed over the sites of the Italian lakes and on to the plains of Piedmont and Lombardy. Round one group of moraines the tide of battle ebbed and flowed in the struggle of Solferino;

another is a memorial of a glacier which passed over the site of Como, up the slopes and over the sandstone ridge enclosing that arm of the lake to the lowland beyond; a third helps to form the lake of Varese; others, farther west, rise like hills from

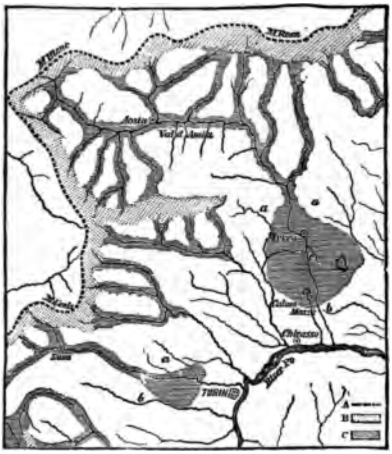


FIG. 7.—Map showing the lines of débris extending from the Alps into the plains of the Po (after Lyell). *A*, Crest of the Alpine watershed; *B*, Névé fields of the ancient glaciers; *C*, Moraines of ancient glaciers.

the plain of Piedmont; the most remarkable and extensive being those opposite to the opening of the Val d'Aoste. This moraine forms a curved chain of hills, with a frontage of over fifty miles, which rise sometimes to a height of more than 1500 feet.

In short, the glaciers of the Alps—and the statement holds good, as will be seen presently, of other mountain regions—are but the dwindled representatives of gigantic predecessors, to which, at any rate on the Swiss lowland, we can hardly refuse the name of ice-sheets.

CHAPTER II

ARCTIC AND ANTARCTIC ICE-SHEETS

LAND-ICE has left its marks on the Alpine region, but in Greenland it is still in possession. The Glacial Epoch belongs to the past in the one, to the present in the other. Every process which has sculptured the surface and formed the glacial deposits of lands wherein a milder climate now prevails, should be found at work in Greenland and the adjacent parts of the Arctic region. Here the results which, in more southern countries, are subjects for conjecture, should be actual matters of fact. Of late years much has been learned about Greenland itself, not only from the members of sundry expeditions to circumpolar regions, but also from the special investigations of Steenstrup, Nordenskiold, Nansen, Peary, and others. From the accounts which have been published we shall endeavour to select those facts which seem likely to throw light on the behaviour and work of ice during a Glacial Epoch.

Greenland is the only very important land mass which, in the Northern Hemisphere, extends beyond the seventy-ninth parallel of latitude. Over almost

the whole region the mean annual temperature is below the freezing-point of water—in the extreme north it is probably not higher than 4° F.—while the cold during the long winter months is intense, the January temperature about latitude 70° being often as low as – 32°. It is not probable that the climate in any part of Europe during the Glacial Epoch was as severe as this, so that we may regard Greenland as exhibiting a picture of cold the effects of which cannot have been outdone in the past history of that continent.

A study of the Arctic regions quickly impresses one fact upon our minds, viz., the markedly unequal distribution of the larger masses of land-ice. This completely covers a very large part of Greenland, while there are few glaciers of importance in Grinnell Land on the opposite side of Smith Sound.[1] The other islands north of the American continent, though some are of a fair size and rise to a considerable elevation, nowhere exhibit an accumulation of ice in any way comparable with that of Greenland. The same is true of the northern part of Siberia; the cold there is no less intense than in the north of the other continent; a very large slice of Siberia is

[1] "A very noticeable feature of Grinnell Land is the paucity of glaciers and the non-existence of an ice-cap, such as prevails in North Greenland. In Grinnell Land, north of latitude 81°, no glaciers descend to the sea-level, which they do in the same parallel on the opposite or Greenland coast of Hall Basin." — *Captain Feilden, Quart. Jour. Geol. Soc.*, xxxiv. p. 567.

included within the annual isotherm of 32° F., no inconsiderable piece within that of 5°, while the January temperature of Yakutsk, in latitude 62° north, is as low as – 40° F., and the soil is permanently frozen to a depth of about 700 feet. Yet in all this region, notwithstanding the intense cold, glaciers are unknown. The reason is simple: the air is dry and the snowfall is but light. So far as temperature goes, a Glacial Epoch rules in Siberia, but no marks of ice action will be left behind in the event of its departure.

Something more, however, is necessary for the formation of an ice-cap, namely, a large land area. A mantle of perpetual snow swathes the islands of the Arctic Ocean—not only those of smaller size on the Greenland coast, but also those, both small and large, to the north of the American continent; yet in none is an ice-sheet found; this seems to require a land mass of almost continental dimensions. The more boldly the district is sculptured, the more easily, *cæteris paribus*, glaciers seem to form. A fairly level island will be merely snowcapped; its shores in summer time may be uncovered and support a scanty vegetation; but in one that rises into mountains, glaciers will stream down the valleys and enter the sea. Still, even here, the amount of ice appears, as might be expected, to be proportionate to the area of the gathering-round. There are important glaciers in Spitzbergen and in Franz Joseph's Land, but these are hardly to be com-

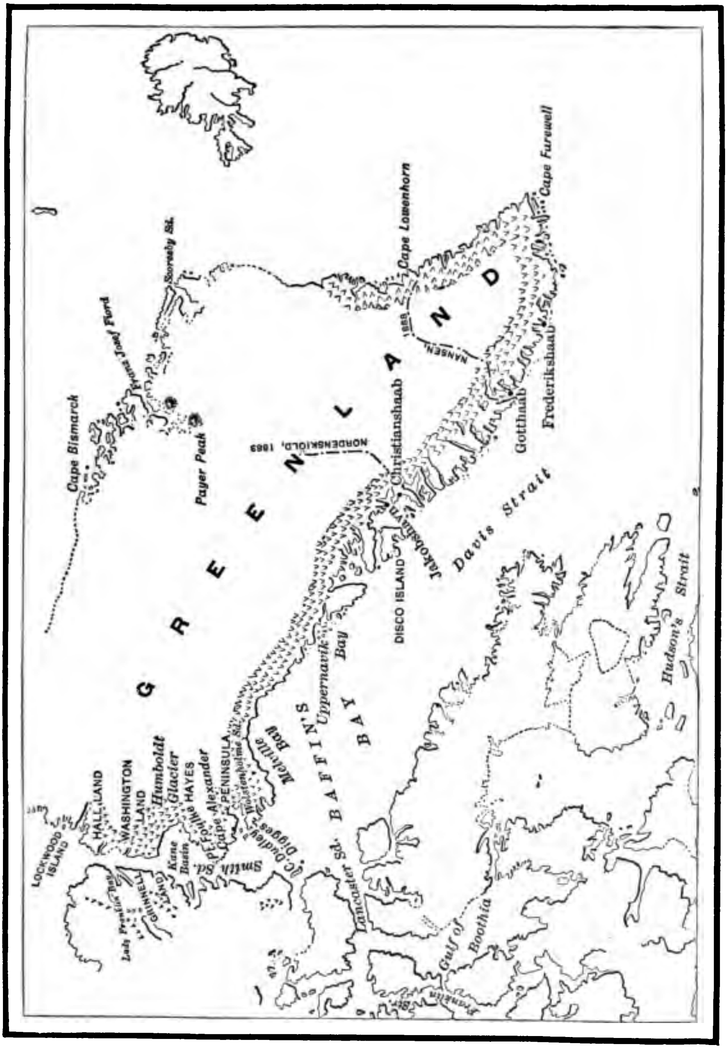


FIG. 8.—Map of Greenland. The arrow-points mark the margin of the ice-field.

pared with the great masses which descend to the sea along every important valley in Greenland.[1] This suggests the question, which will be discussed in a later chapter, viz., how far is the sculpture of Greenland and other Arctic regions due to the action of ice? For if the latter has modified, rather than determined, the physical structure of the country, there must have been a time when Greenland was comparatively, if not wholly, free from snow and glaciers. At the present time, however, it affords a picture of a land where the Glacial Epoch is dominant, though perhaps even here the ice-tide is ebbing. Let us glance first at the southern half of the region, and take as an example that part of the western coast which is south of latitude 71°. In geographical position it corresponds roughly with the portion of Scandinavia which lies between the North Cape and Bergen. The comparison, however, may be pressed further. Such as Greenland is now, Norway has been; the former, if the great ice-sheet which now masks its interior were reduced to a few isolated glaciers, would probably present a very close resemblance to the latter. Norway also is pierced with fjords; it is fringed with islands;[2] it is a region of

[1] The total glacier surface (ice and snow) of the Alps is estimated at from 1158 to 1544 square miles. That of the Justedal in Norway is alone about 347½ square miles, being larger than any single region in Switzerland, and the ice-covered area of Greenland is not less than 320,475 miles. *Alpine Jour.*, xii. 226.

[2] These are frequent, though perhaps less numerous on the Greenland coast; the resemblance might be more complete if Norway were upraised two or three hundred feet.

huge fells and of bold rocky hills; their craggy flanks descend steeply to the coast, their cliffs often overshade the quiet recesses of the fjords; even the very islands are hilly. The same appears to be true of Greenland. The land rises rapidly from the water's edge to a height of from two to four thousand feet; for a considerable distance inland the continuity of the ice is often interrupted by projecting masses of rock, the remnants of buried mountains, which sometimes rise full a thousand feet higher.[1] Thick as the ice may be, it evidently swathes a hill-region. The undulations of its surface indicate the contours of the buried land, and each of its huge glaciers marks the course of a valley. The configuration of the ground in the interior of Greenland is a matter for conjecture. Nansen, in crossing the inland ice at about latitude 63°, found no sign either of mountain ranges or of any marked inequality. He traversed a huge plateau, at a height of from 8000 to 9000 feet above the sea, which for many miles was as nearly as possible level, and from which frozen snow shelved gently down eastwards and westwards.[2] The greater

[1] The Nunataks, as these projecting summits are called, visited by Nansen, are about 47 miles from the edge of the ice, and are about 5400 feet above the sea, the level of the ice surface being about 4200.

[2] The "divide" (practically a plain 8970 feet above the sea-level with a gentle rise towards the north), where crossed by Dr. Nansen, was about 226 miles from the west coast, and 126 from the east. On this side the average gradient was, at first, 1 in 23; on the other, 1 in 42; but the slope then became less, and gradually died almost away towards the interior.

part of the ascent to the higher portion, and of the descent from it, is over a vast field of sloping or gently undulating snow.[1] The contours of the buried region are perceptible only in the more immediate neighbourhood of the coast, and probably cannot be detected beyond about a hundred miles from it. Here the "Nunataks" begin to emerge from the ice and to rise above its surface like islands from a sea. On approaching these from the interior, the undulations of the snowfields assume a more definite plan, and their slopes converge towards a broad shallow basin-like depression, which gradually deepens till the ice at the lower end runs like a broad causeway rather below the general level of the district. Here then the great central reservoir of ice is tapped by a definite drainage channel. This is the birthplace of one of the great glaciers. The ice no longer presents a smooth unbroken surface; crevasses become more frequent; travelling over it is at once more difficult and more dangerous. The scenery in one of these basins, though on a far grander scale, recalls that of the gathering-ground for one of the larger Alpine glaciers; such, for instance, as the névé of the Great Aletsch or the snow plateau which is the source of both the Gorner and the Findelen glaciers. In regions like the Alps, where the mountains rise more steeply than in Greenland, lateral glaciers form among the rocky ridges on either side of the great

[1] Here the breadth of the continent is about 350 miles.

trunk-stream; these sometimes become its tributaries, though often, when their own gathering-ground is small, they melt away before reaching it. If so, their terminal moraines are spread out on the steep slopes, but occasionally may be confused with the lateral moraine of the trunk-stream. Such glaciers are less conspicuous features in Greenland scenery, owing to the greater depth of the ice and the more monotonous contours of the spurs separating the valleys; but occasionally an offshoot from the main mass of the inland ice may pass through the depression between two "Nunataks" in the direction of the great effluent, the surface of which is already lying at a lower level. Thus the offshoot becomes relatively a tributary glacier, though from a common source, and the result of this is curious. No moraines can be seen on the inland ice, not even a solitary erratic spotting its pure white surface. These only make their appearance in the region of "Nunataks" and of valley glaciers. Even here they are generally insignificant compared with those on the glaciers of the Alps. The reason is obvious. Where no rock rises above the ice, no fragments can fall upon its surface; the possibility of a moraine ceases with the last "Nunataks," and as these are not large, the stream of blocks which they originate must be correspondingly small. Still, in a few cases, piled-up heaps of stone occur on the ice farther inland than might have been expected. One such

was observed during Nansen's expedition in the neighbourhood of the "Nunataks" which bear his name. The moraine was full 4000 yards in length; apparently it was about 500 feet high, but this magnitude proved to be illusory, for the débris was little more than a veneer to a hidden mound of ice, which had been screened by the material and thus kept from melting. Still, not only was this moraine larger than might have been expected from the size and character of the adjacent "Nunataks," but also the blocks on it were all subangular and polished. In other words, the material of which it was composed had travelled not upon, but beneath, a glacier. Its presence may be thus explained: an offshoot from a higher part of the main ice-sheet had passed between two of the "Nunataks" toward the surface of the trunk-stream below, and on this surface, which it had just succeeded in reaching, it had deposited its terminal moraine; this, however, as few blocks, if any, came from the adjacent "Nunataks," consisted of débris which had travelled beneath the ice, and thus bore the usual indications of such a passage.[1]

So far as can be ascertained, the quantity of this "ground moraine," even in Greenland, usually is not great. In one respect the estimation of it should be comparatively easy, because the configuration of the surface is not favourable to the accumulation

[1] From what source this may have been derived will be discussed later.

of much superglacial material, even when the ice-sheet terminates in valley glaciers which are bounded by steep and rocky slopes. Thus in Greenland moraines are comparatively inconspicuous about the smaller glaciers of the mountainous border-land, since it, like Norway, is commonly much less rugged than Switzerland. In the case of the great trunk-streams of ice, the exact quantity of subglacial material is difficult to estimate, because they almost invariably end in fjords, their steep ice-cliff rising for some hundreds of feet above the water and from considerable depths below it. But whenever one of the smaller offshoots from the inland ice is melted away before reaching the sea, as sometimes happens, it appears not to leave behind any large amount of ground moraine. In some cases the glaciers have retreated, leaving, not a thick sheet of clay mixed with boulders, but merely a few scanty patches on a bed of bare rock: the tract differs from that deserted by a Swiss glacier only in the greater flatness of the ice-worn surfaces, and the general absence of angular débris. Nevertheless a considerable quantity of mud and a number of stones must be constantly travelling beneath the Greenland ice, and these, under certain circumstances, may accumulate: the most favourable, apparently, will be when a glacier, which ends either on flattish ground above the sea-level or in very quiet water, remains for a considerable time almost stationary, and then very

slowly retreats. Thus the material of its ground moraine, though inconsiderable in amount at any one moment, accumulates to form a kind of terminal moraine, and this is drawn very gradually, like a coverlet, over the bed of the valley. In the same way lateral moraines of a similar character may be occasionally constructed of material extruded from beneath the ice.[1]

A fact which may prove to be of some importance may be noticed in passing. These huge ice-streams, though fed from the vast mass of inland ice, seldom or never protrude seawards. The valley which they occupy ends as a fjord, often several miles in length, down which the bergs detached from the great terminal cliff of the glacier drift slowly to the open sea. Even in Eastern Greenland, where the climate is more rigorous, the same rule holds as to the absence of ice from the coast. For instance, the great fjord called Scoresby Sound (about latitude 71°) stretches far inland, and even branches out into tributary water-valleys, like the Sogne Fjord in Norway, the heads of them being closed by a tongue of the inland ice

[1] Nordenskiold ("Arctic Voyages," p. 169) describes a district near Disco Bay which had been recently abandoned by the land-ice as curiously like the woodless gneiss districts in Sweden and Finland. "Everywhere occur rounded, but seldom scratched, hills of gneiss with erratic blocks in the most unstable positions of equilibrium, separated by valleys with small mountain-lakes and scratched rock-surfaces. On the other hand, no real moraines were discoverable. These, indeed, seem to be commonly absent in Scandinavia, and are, generally speaking, more characteristic of small glaciers than of real inland ice."

which terminates in a huge cliff. But though for five months in the year the mean temperature in this district is below the zero of Fahrenheit, though the land between the valleys rises abruptly to an elevation which frequently attains 4000 feet, and occasionally is considerably higher, bare ground during the summer season is not uncommon on the upper plateaux, while it is the rule in the lower regions near the coasts. Reindeer and musk-sheep, hares and lemmings (not to mention predaceous animals, such as bears, foxes, and ermines), are fairly numerous, showing that the district must produce a considerable amount of herbage.[1]

Almost everywhere the lower ground near the coast seems free from permanent snow. This indeed will gather, as it does in the Alps at from eight to nine thousand feet. The hills rise from the lowland with comparative abruptness to heights of several hundred, or even a couple of thousand feet; but the ice-sheet seems unable to travel beyond the margin of that region, though its surface in the interior is far above the general level of the bordering hills, and it only threatens to trespass on the lowland when it is gathered together into a valley. Hence it appears probable that a very large portion of the inland ice, if not actually at rest, moves with extreme slowness, and that it only advances with any

[1] Lieutenant Ryder's East Greenland Expedition. *Geog. Jour.*, 1893, vol. i. p. 43.

approach to rapidity when the underlying valleys become larger and better defined. One curious effect, due to the advance of some tongue of the inland ice, may be mentioned here, namely, that it may intercept the course of a small river fed from another portion of the ice-sheet, and thus, as occasionally happens in the Alps, may dam up the water and produce a lake of some magnitude.

This coast also, like the western one, affords indubitable evidence that the amount of ice in Greenland is less at the present time than at some earlier epoch. In the neighbourhood of Scoresby Sound, according to Lieutenant Ryder's report, moraines, glacial striations, and *roches moutonnées* are met with everywhere without the margin of the inland ice, even on the tops of plateaux at a height of 4300 feet. Whether this retreat is due to a rise in the temperature or to a diminution of the snowfall cannot be determined. At the present time, the amount of precipitation on the west coast of Greenland near latitude 70° is about 12 inches.[1] This is rather small; but farther inland the vapour will descend as snow, and the amount very probably may be greater. Dr. Nansen experienced frequent snowstorms even on the highest part of the great dividing plateau. But in a climate such as Greenland, where not only the cold is great for so

[1] Rink, quoted by R. Brown, *Quart. Jour. Geol. Soc.*, xxvi. (1870), p. 681. But farther south the rainfall, according to statements in J. Hann's *Klimatologie*, is much higher, reaching about 51 inches at Iviktut (lat. 61° 12′).

large a part of the year, but also the rays of the sun—even though in the summer season it "sets into sunrise"—strike the surface very obliquely, the loss by evaporation must be small, so that almost all that falls accumulates. The surface of the snow during the later part of August and the earlier part of September was found by Dr. Nansen to be permanently in a "dusty" condition above the level of 7000 feet, and he expresses the opinion that on the major part of the inland ice there is no surface melting of the snow.

The rest of Greenland, farther north, so far as it is known, corresponds generally with that which has been described, though the cold is yet more intense and the area occupied by ice and snow is proportionately somewhat larger. The physical structure of the country appears to be generally similar; nevertheless, the inland ice, except in the fjords, does not come down to the sea-level, and even here it is arrested by the water before it can reach the portals of the valley.[1] Its general features have been ascertained by Lieutenant Peary's adventurous journey across the northern end of Greenland.[2] After wintering in latitude 77° 43′ N., he travelled across it from M'Cormick Bay to its northern edge in 81° 37′ 5″, a journey of 650 miles. From this spot he followed the coast southwards for about 26 miles to Independence Bay, and

[1] Even the gigantic Humboldt Glacier, though its sea face, an ice-cliff from 300 to 500 feet in height, is 45 miles long, lies very slightly back from the general outline of the coast.

[2] *Geog. Jour.*, 1893, vol. ii. p. 304.

thence recrossed the inland ice at a height of about 8000 feet above the sea-level. The vast ice-streams at the head of Petermann, of Sherard Osborne, and of other fjords on the north-western coast, can be traced back inland for distances of from thirty to fifty miles, widening out fan-fashion into huge glacier basins. These are divided by rounded upland spurs, which rise for about 5000 to over 6000 feet above sea-level, while the basins themselves are only from 3500 to 4200 feet above it. The ice in the latter is much crevassed, in consequence of which Lieutenant Peary was compelled to keep much farther away from the coast than he had purposed. No crevasses, however, were encountered beyond the limit of the glacial basins. From the central divide the inland ice slopes very gently towards the north.[1] So gradual is the decline in the western direction, that Lieutenant Peary on his return journey had to travel for thirty miles before he could be certain that he was really descending. The inland ice, however, which he quitted at the most northern point, terminated above the coast in a more rapid slope, namely, about 1 in 2.6. Even here the zone of land bordering the sea was free from ice. It was not a dead level, but a tract diversified by hills and valleys; its surface being strewn with boulders and covered with small angular

[1] The rise from the northern edge of the ice-cap was at first 1000 feet in 10 miles, next 1300 feet in 21½ miles, and then 1000 in 20 miles—or, approximately, 1 in 50, 1 in 83, and 1 in 100.

stones, which appear to have been cemented by the pressure of the ice which formerly had crept over it. Grasses and flowering plants were plentiful in places, and musk-sheep were abundant; at least four species of birds were seen, with humble-bees, butterflies, and many flies. Though the sea was ice-covered, land was visible to the west and north-west from the most northern point attained, on which no sign of an ice-cap could be discerned.[1]

Captain Feilden's examination of the coasts of Smith Sound, between latitude 79° and 82° N., supplies some other particulars which throw much light on the history of a coast-region during a Glacial Epoch. He writes thus[2]: "Sub-aërial denudations of the surfaces of the cliffs cause vast masses of material to fall during the thaw of the short summer, on a scale so gigantic that the mind fails to realise it unless it has been actually witnessed. The base of the cliff is concealed by a talus, made up of a shifting mass of material resembling those known as screes in the English Lake district, and, like them, chiefly supplied by fragments from the deep gullies or 'rakes' which seam and scar the cliffs above, and act as channels for the passage of the frost-worn material of the uplands. The destruction of rock is not merely confined to

[1] Lieutenant Peary observed that the wind blew pretty steadily from the centre of the divide, as it is found to do at this season of the year in anticyclonic regions. Snow not unfrequently fell, and fog on the summit showed that even there the air was not free from moisture.

[2] *Quart. Jour. Geol. Soc.*, xxxiv. (1878), p. 563.

these particular lines of erosion, but is continuous over the whole surface of the country during the episodes of summer thaw. In those climates the approach of winter is not marked by any transition. Beyond the limits of perpetual snow the land at the close of the transient summer is saturated with moisture; the fissured precipice, the cleaved slate, and the gravel-bed are charged alike with water to their utmost capacity; without any warning, winter lays her icy hand on the scene, and in a few hours the face of Nature is changed, and moisture and running water are converted into ice. The destructive force exercised upon rocks during the progress of expansion throughout the entire Polar region is a most potent factor, and gives results but little comparable with the sub-aërial work now going on in temperate climes. On the first signs of thaw large masses of rock, separating along lines of weakness formed by planes of jointing and bedding, are detached from the cliff, and falling on the screes, slide down to the ice-foot beneath, the impetus being often sufficient to carry them on to the floe, where they remain until the general break-up of the ice, when vast quantities of material are drifted seaward.

"The ice-foot appears to be formed, not so much by the act of freezing of the sea-water in contact with the coast, as by the accumulation of the autumn snowfall, which, as it drifts to the beach, is met by the sea-water at a temperature just below the point

of freezing of fresh water, and instantaneously converted into ice, forming a solid wall from the bottom of the sea. This wall is constantly increasing in height from snowfalls. When the young ice, or season floe, is formed at the surface of the sea adjacent to the ice-foot, there is little difference between the level of the floe and the ice-foot; but as the latter is constantly increasing in height, and the former is twice daily oscillating with the change of tides, it is easy to see how a line of junction is impossible; and the height of the surface of the ice-foot above the level of high water is mainly dependent on the amount of snowfall, while its depth below that level is dependent upon the slope of the sea-bottom and the vertical range of the tides. It is almost needless to observe that on exposed and projecting headlands, the ice-foot, like the beaches of temperate regions, is invariably absent.[1] . . . The typical aspect of the ice-foot in Smith Sound is that of a terrace of fifty to a hundred yards in width, stretching from the base of the 'scree' to the water's edge. . . . Sea-ice driven on shore by gales, or moving up and down with the tides, is a very potent factor in glaciating rocks and pebbles. Along the shores of the Polar basin this process of glaciation was seen in progress. . . . At the south end of a small island

[1] The sentences omitted refer to the part taken by the ice-floe in the formation of the beach terraces, which are here, as in other parts of the Arctic regions, notable features in the scenery.

in Blackcliff Bay (latitude 82° 30′ N.), the bottoms of the hummocks, some eight to fifteen feet thick, were studded with hard limestone pebbles, which were rounded and scratched as distinctly as others taken from moraines; when extracted from the ice, only the exposed surfaces, as a rule, were glaciated. As the tide recedes, the hummocks do not always arrive at a position of rest without some disturbance of the subjacent material, particularly on a shelving shore, and the sliding of the hummock to a lower level, and the sound following on the grating together of the pebbles beneath, may be noted. In many places where gaps occurred in the lines of ancient sea-terraces, the basement rock, as well as some of the pebbles in the terraces, were found to be glaciated, and there can be no doubt that this is due to the action of shore-ice, the condition of the terraces precluding the idea that it might have been the result of glacier action. Pushed up mounds or long ridges of gravel, both at the sea-level and at various elevations, are a conspicuous figure along the shores of the Polar basin; these sometimes extend at the edges of deltas in long lines of mounds like giant mole-hills."

Captain Feilden also called attention to the fact that Grinnell Land has been uplifted to an altitude of 1000 feet above sea-level within a time so recent that no change could be detected in its flora and fauna, terrestrial and marine. Raised beaches and sundry other proofs of very considerable elevation

have been also observed on the opposite coast of Smith Sound and in other parts of Greenland, as well as in Nova Zembla (to a height of 600 feet above sea-level), in Franz Joseph's Land, Spitzbergen, Siberia, and the north of Norway. In short, the land appears to have risen in the Arctic region often to a height of some five hundred feet, more or less, and occasionally to a considerably greater elevation. This too, in some cases, has happened since the ice has disappeared, or at least greatly diminished.[1] It is therefore obvious that in all speculations as to the condition of any region during the Glacial Epoch, account must be taken of the possibility of a not inconsiderable difference in either direction from its present level.

Further illustrations of the conditions prevalent during a Glacial Epoch may be also expected from the Antarctic regions. Of the latter, however, much less is known, for hitherto comparatively small success has rewarded the attempts at exploration. The climate here appears to be more inclement than in the corresponding parts of the northern hemisphere. The sea, even in the summer months, is often encumbered by drifting ice, which renders navigation both difficult and dangerous. Even in latitude 66° 55′ S., the vessel of Sir J. C. Ross, on his noted voyage, was completely surrounded by the "pack." The bergs

[1] There is also evidence to show that in some places the latest movements have been in the opposite direction ; see, for cases of both, R. Brown, *Quart. Jour. Geol. Soc.*, xxvi. 1870, p. 690.

also were often of enormous size; their tabular summits, "bounded by perpendicular cliffs on all sides," rose from 120 to 180 feet above the water, and several of them were estimated as a couple of miles in circumference.[1] More than once he would have been beset had he not steered northwards. In most parts explorers have not succeeded in penetrating much beyond the Antarctic circle, and it is probable that very much of the region within the latitude of 70° S. is occupied by land. Opposite to South America, and to almost the whole of Australia, land or groups of islands extend somewhat north of the Antarctic circle, but about longitude 171° E. Sir J. Ross's exertions were rewarded by exceptional success. From about latitude 70° to 79° S. he found comparatively open water, and sailed along near the coast of a great mass of land, on which, however, it was impossible to set foot. Its shores were everywhere covered with ice projecting into the sea. A thick mass of ice capped the whole region, and bare rock was only seen where precipices rose high above the water. Mile after mile this unbroken rampart, often rising to a height of from two to three hundred feet, presented a hopeless barrier to the explorers. It evidently indicates the margin of a large and mountainous mass of land, perhaps of an Antarctic continent. From the top of the ice-cliff the dazzling

[1] Ross, "Voyage of Discovery and Research in the Southern and Antarctic Regions," vol. i. chap. vii.

white surface sloped up towards a range "whose lofty peaks, perfectly covered with eternal snow, rose to elevations varying from seven to ten thousand feet above the level of the ocean. The glaciers that filled their intervening valleys, and which descended from near the mountain summits, projected in many places several miles into the sea, and terminated in lofty perpendicular cliffs. In a few places the rocks broke through their icy covering, by which alone we could be assured that land formed the nucleus of this, to appearance, enormous iceberg." This description relates more particularly to the part between latitude 71° and 72°, but even higher summits were seen farther to the south. Mount Erebus, an active volcano rather south of latitude 77°, was estimated as about 12,400 feet high, and Mount Terror, an extinct cone to the east of it, is only about 1500 feet lower. From near that spot "a perpendicular cliff of ice, between 150 and 200 feet above the level of the sea," extended as far as could be seen, and a long way back from this the summit of a lofty mountain range was visible, which passed beyond the 79th parallel of south latitude. Some places, however, were occasionally accessible—as, for instance, Possession Island, in latitude 71° 56′ S., and Franklin Island, in latitude 76° 8′ S. Both are formed by volcanic rock, and, though destitute of vegetation, are not permanently snow-clad. At a few miles from land the depth of the sea, as ascertained by soundings, was

generally less than 200 fathoms. The bottom was usually a greenish mud; small stones were sometimes noted; boulders also must have been present, for they were often seen upon the drifting ice. One berg, which had "turned turtle," and thus exposed a new surface, was so thickly covered with earth and stones that at first it was mistaken for a small island. The temperature of the air was almost invariably low. "During the two summer months (January and February) of the year 1841 the range of the thermometer was between 11° and 32° F., and scarcely once rose above the freezing-point."[1] South of latitude 60° this reading seems rarely to be exceeded. The surface of the sea was found to be correspondingly cold, but the temperature increased with the depth; in one instance, when it was 31° on the surface, it gradually rose till, at 600 fathoms, it had reached 39.8°.[2]

More recent explorers have added to our knowledge of the Antarctic regions, but have not materially altered the general conclusions suggested by Sir J. C. Ross's narrative. The southern pole, according to the excellent summary given by Dr. J. Murray,[3] is probably surrounded by a continent even larger than Australia, *i.e.*, nearly 4,000,000 square miles in area. Its form is somewhat irregular. The land, so far as is known, seems often to correspond with the part

[1] Sir C. Lyell, "Principles of Geology," chap. xii., where other instances of the character of the Antarctic region are given.

[2] At 150 fathoms, 35.2°; at 300, 37.2°; at 400, 38.8°.

[3] *Geog. Jour.*, 1894, vol. i. p. 1.

described by Ross. It rises sometimes rather rapidly from the sea, chains of hills ranging from 3000 to 7000 or 8000 feet not being uncommon, some peaks attaining considerably greater elevations. These are covered with ice more uniformly and to a greater depth than in Arctic regions, crags but seldom interrupting the white swathing, while, even at the coast, bare lowlands or rocky cliffs are not common. The islands, however, in the summer time are comparatively free from snow. The ice-sheet descends from the slopes into the sea, and occupies its bed to a considerable depth, the thickness of the mass being doubtless affected by the configuration of the buried land. From this ice-sheet the great tabular bergs, so characteristic of the Antarctic Ocean, are detached, and the ice-cliffs are formed which guard the secret of the interior region. The ice probably not seldom attains a thickness of from 1200 to 1500 feet, and occasionally exceeds this opposite to the openings of the more important valleys. It is, however, doubtful whether, as a rule, 2000 feet is exceeded.[1] In Antarc-

[1] Dr. Murray is of opinion that the thickness of the ice does not generally exceed from 1600 to 1800 feet. As the height of the floating bergs is stated to be from 150 to 200 feet above the water, the total thickness of the mass would be about ten times this amount (for a rectangular block of ice would float in sea-water with about nine-tenths of its mass submerged). Dr. Murray repudiates Dr. Croll's suggestion that the ice at the south pole would be from 10 to 20 miles thick. In a region like this it is almost certain that the precipitation would diminish greatly in amount in proceeding from the coast zone. In the interior (assuming that no important mountain chain exists) there would be a nearly level plain of snow as in Greenland, and of much greater extent.

tic regions the amount of precipitation appears to be greater than in Greenland, so that in this respect they are rather more helpful in giving an idea of the condition of parts of Europe at a period of extreme cold. For instance, Scandinavia, in the Trondhjem district, might have formerly presented some resemblance to the region round Erebus and Terror Gulf, where the glaciers (according to Dr. Donald) cannot exceed a thickness of about 700 feet at their ends. It must, however, be remembered that the great ice wall does not generally come farther south than latitude 70°, so that in the Antarctic region comparisons must be made, not with Scandinavia, but with that part of Greenland which lies to the north of Disco Bay.

The sea is frozen over during the long winter of either Polar region; the thickness of the floe-ice, as it is called, obviously depending upon the latitude and various local circumstances. In Baffin's Bay, for instance, it averages five or six feet, pieces of eight or ten feet thick being rare. But around Spitzbergen it not unfrequently ranges from twenty to thirty feet, and sometimes even gets near forty. On the approach of summer, the frozen surface of the sea, which is constantly liable to local fracture owing to the rise and fall of the tide and the effects of gales on the uncovered water, breaks up and floats towards the warmer regions. Interspersed with bergs detached from the ends of glaciers, this ice makes the "pack," which for a considerable time is

a formidable obstacle to navigation, and sometimes places an insuperable barrier between the more open seas and the land, though at last it gradually drifts away. But even as it drifts, it may again accumulate locally. Baffin's Bay, for a space of nearly 200 miles between Davis Strait and the opening of Lancaster Sound, is liable to be blocked in the later part of the summer by the "Middle pack." This accumulation comes to an end in the central part slightly to the north of latitude 65°, but it extends along the coast on either side at least five degrees farther south.[1] As the floe-ice forms upon open water, it cannot, as a rule, transport much débris, but occasionally, as already stated, materials from the land may lodge upon it by slipping beyond the limit of the ice-foot. The latter, however, is a most important vehicle for the transport of material. Into its lowest part, the boulders, gravel, and sand of the shore are frozen; into its mass, débris of all sizes, from mere earth to great fragments of the cliffs, is incorporated or embedded; because falls from these are most abundant early in the winter, after which time the thickness of the ice-foot must be considerably increased. Upon its surface a final shower will probably be scattered by the approach of spring before the ice-foot ultimately breaks up and floats

[1] In the Southern Hemisphere the pack ice seems to be even more widely spread and a no less formidable obstacle. The sea is often completely covered with floating ice, which may make navigation impossible down to about latitude 65°.

away. Its fragments might be called huge rafts, if by this term the amount of cargo which they carry, as it were, in their hold was not ignored, while to call them ships is to lose sight of their form. The bergs also transport material above, within, and below, the relative amounts depending of course upon the configuration of the land on which the parent glaciers have been formed. The material in the last of these cases, as a rule, is only attached to the surface, and so is likely to be speedily dropped and deposited.

The transporting power of ice is very considerable, especially in sea-water.[1] As a general rule, a cubic yard of ice will just support a cubic foot of average rock without sinking; thus a granite boulder, 6 feet long, 3 feet wide, and the same in thickness, would not be too heavy a cargo for a piece of floe-ice 20 feet long, 15 wide, and 5 thick. The quantity of material thus transported must be far from small. The greater bergs, it is true, do not appear to embed a large amount of débris, or to carry very much on their upper surface, owing to the peculiar conditions of the region, but the bergs from glaciers enclosed by craggy ridges, like those of Spitzbergen, must do more in this respect, while the ice-foot evidently is an agent of considerable importance. Even the great bergs of the Antarctic regions, accord-

[1] The specific gravity of ice is about .918, of sea water 1.026 (slightly higher in warm regions), and of average rock 2.7.

ing to Sir J. Hooker, probably contain boulders or earth in all parts of their mass. The distance also to which material may be carried by floating ice is very great. In summer time bergs and the remnants of floe-ice are common on the western side of the Atlantic as far south as the latitude of Turin.

Such, then, is a brief summary of the facts collected by Arctic explorers. They seem to lead to the following conclusions:—

(1.) Certain conditions must exist before an ice-sheet can be formed. These are: (*a*) a climate so severe that the mean annual temperature is below 32°; (*b*) a fair, if not a considerable, amount of precipitation, chiefly in the form of snow; and (*c*) a large land area to act as a gathering-ground.

(2.) Glaciers, however, may form upon islands of moderate size, provided these are mountainous; snow and ice may swathe the higher parts of a lowland, and may cap fells or tabular mountains; but in such cases the covering remains practically at rest. An outward movement in the mass appears not to commence until it has occupied an area of some considerable extent, and this movement is obviously facilitated when the ground has a distinct slope, and most of all when the region is furrowed by well-marked valleys. The Scandinavian peninsula, under suitable conditions of temperature, would probably present a rather close resemblance to Greenland at the present day. But in any speculations as to the

extent of its ice-sheet, we must remember that this region is generally narrower than Greenland, and that the upland district would not be materially enlarged by an elevation sufficient to convert the Baltic and most of the North Sea into dry land.

(3.) When a region is washed by the sea, the ice-cap only descends to the water's edge under rather exceptional circumstances, such as unusual accumulation, concentration of the product of a large drainage area (as is the case opposite to the mouth of a valley), a steady slope of the buried land up to a considerable feeding-district, and the like. The lower ground in the immediate neighbourhood of the coast, and the smaller islands, are generally free from a permanent covering of snow and ice.

(4.) In the case of a land thus washed, the action of the shore-ice may produce results locally very similar to those of a glacier, and the amount of material transported by floating ice (sometimes to long distances) is often very great. When the coast is steep, but its rocks consist of material rather easily detached and liable to slips, very large fragments may be thus conveyed.

The facts summarised in this and the preceding chapter enable us to form a general idea of the conditions prevalent and the processes at work during a Glacial Epoch. This phrase obviously postulates the existence of two conditions: a mean annual temperature not exceeding 32° F., and a fair amount

of precipitation, necessarily for the most part in the form of snow. Supposing the former condition fulfilled, a great accumulation of ice may be the result of moderate precipitation with a very low temperature, or of a larger snowfall with a somewhat milder climate.[1] An ice-sheet demands a large area of land, and forms most readily when this is a hilly upland plateau, like parts of Norway at the present day. A region of huge rolling fells is more favourable than one broken by precipitous ranges, rising into lofty peaks and furrowed by deep valleys. The latter is a region of glaciers, however gigantic, rather than of an ice-sheet; though obviously these glaciers for a certain distance outside the hill-country may become confluent. A fairly marked though gradual upward slope seems the most favourable to a general extension of the ice from its central gathering-ground. Proximity to the sea, though helpful in increasing the amount of precipitation, tends to restrict the advance of the ice. The difference between the condition of the Arctic and the Antarctic coasts is probably due to the heavier precipitation in the latter, and the more uniform and steep slope of

[1] This probably produces an effect in Greenland. At Iviktut (latitude 61° 12′, mean temperature 32.90° F.) the rainfall, as already stated, is 51.1 inches; at Godthaab (latitude 64° 10′, temperature 27.68°) it is 26.7 inches; at Upernavik (latitude 72° 48′, temperature 12.02°) it is 12.6 inches. On the inland ice the precipitation is probably greater than near the shore, but such evidence as we possess suggests that it is far from heavy over the more northern part of Greenland.

the surface. Thus, not only its valley glaciers are on a more gigantic scale than those of Greenland, but also every slope becomes an ice-field, and the overlying mass moves everywhere outwards and downwards, trespassing upon the bed of the sea.[1]

The glaciers of Mont St. Elias, in Alaska, are in some respects intermediate between the ancient glaciers of the Alps and the existing ice-sheet of Greenland. Of late years they have been studied by exploring parties from the United States, and the results obtained may throw light upon some of the problems mentioned in the remainder of this book. To quote the description of M. I. C. Russell,[2] who was in charge of the exploring party in 1891, the great Malaspina Glacier is one of those for which the name of a Piedmont glacier has been proposed—that is, it is formed by the union of several ice-streams, which descend separately from the mountain and unite at the base. It covers an area of about 1500 square miles; but it differs from the old Alpine glaciers in this respect, that in one place it comes down to the sea, where it terminates in cliffs sometimes 300 feet in height, Mont St. Elias rising to an elevation of about 18,100 feet.

Mr. Russell describes it as "a vast, nearly hori-

[1] The observations of the depth of the sea within a comparatively short distance of the margin of the Antarctic ice seem to indicate that the ground generally shelves steadily downwards, and that the slope visible above water is continued for some hundreds of feet below it.

[2] Thirteenth Annual Report of U.S. Geol. Survey (1891–92), Part II. p. 7.

zontal plateau of ice. The general elevation of its surface, at a distance of five or six miles from its outer border, is about 1 500 feet." The central part is free

FIG. 9.—Malaspina Glacior.

from moraines, or dirt of any kind, but is much shattered by crevasses.

The lower part of the Malaspina Glacier is interrupted by two groups of hills, respectively named by the explorers the Chaix and the Samovar Hills. Mr.

Russell thus describes the former:—They are "about ten miles in front of the vast southward-facing precipice of the St. Elias range," and "rise through a sea of ice, the shores of which cannot be seen for their summits." They are "geologically unique . . . formed of a monoclinal block of conformable strata eight or ten miles long, trending north-east and south-west, and tilted northward at an angle of 10 or 15 degrees. The general elevation of their crest is about 3000 feet, while the sharp pyramids that give them a serrate outline rise 200 or 300 feet higher. The southern face is precipitous, and so steep in most places that it cannot be climbed. The northern slope is gentle, conformable with the dip of the strata, and has an undulating, hummocky surface, covered with low but very dense Alpine vegetation. The southern face is too steep and disintegrating too rapidly to support vegetation, except on a few of the buttressing ridges, and about the immediate base, where there is a dense forest of spruce-trees.

"Owing to the softness of the material of which the hills are composed, it is easily eroded, and presents typical illustrations of rain and wind sculpture. The familiar forms, originating in heaps of clay when exposed to heavy rains, are there reproduced on a grand scale. . . . The topographic form of the hills is sufficient in itself to indicate their extreme youth. Although composed of soft, easily eroded shale, they stand as sharp ridges surmounted by angular pyramids

indicative of immature sculpture. Under the climatic conditions to which they are subjected, it is evident that a few centuries would be sufficient to greatly reduce their height and to round their contours. This indication of youth is also sustained by the fossils with which many of the strata are charged, which are of living marine species.

"But what makes the hills especially interesting to the geologist is the fact that they are composed of stratified morainal material. The stratification is conspicuous even from a distance, but is due principally to slight changes in colour. Light purplish-brown alternating with light grey are the prevailing tints. The colours are in broad bands, which may be traced continuously for thousands of feet. Knowing the elevation of the southern precipice, one can easily estimate the thickness of the strata there exposed. From many eye-estimates, it is evident that the minimum thickness of the deposit cannot be less than 4000 or 5000 feet. The rocks are essentially homogeneous from base to summit, and are composed of sandy clay containing large quantities of both angular and rounded boulders, of all sizes up to 6 or 8 feet in diameter. The boulders are composed of many kinds of rock, and represent as great a variety as do the stones in the moraines on the living glaciers with which the hills are encircled. They are not arranged in definite strata, but occur throughout the deposit from base to summit. Some of them are faceted,

polished, and striated in a manner indicative of glacial action. The fact that they have been transported by glaciers is beyond question.

"In the finer portions of the deposit, especially in certain fine light grey sandy clays, sea-shells are numerous.[1] . . . Besides the shells of molluscs, there are the shell-cases of annelids (*serpulæ?*), attached to glaciated boulders, showing that the stones on which they grew must have remained exposed at the bottom of the sea for some time before being wholly buried.

"The interpretation of these various records leads to the conclusion that the strata composing the Chaix Hills were deposited about the extremity of a glacier which ended in the ocean. Portions of the finer material, especially that containing sea-shells, is largely glacial silt, while the boulders and gravel were deposited by the bergs that floated away from the face of a glacier. The deposit now forming at the extremity of the western lobe of the Malaspina Glacier, where it breaks off into the sea, must be very similar to the strata forming these remarkable hills."

The Samovar Hills, to the north-east, and a third group, named the Robinson Hills, about in a line with the southern escarpment of the Chaix Hills, consist of like material and agree in structure and dip. "The fact that these three uplifts have the same monoclinal structure, and about the same direction of dip,

[1] A small collection was made. It contained eleven species, all still living in the adjacent ocean.

and the same general trend, indicates that they are closely related in their origin. In my judgment they were formed by the uplifting of the northern side of a fault, or of a series of closely related faults, and received their northward inclination from the tilting of the uplifted blocks."[1]

Another point of interest, noticed also by earlier explorers, is exhibited where the glacier reaches the sea. Here, to quote Mr. Russell's words, "the bottom of Malaspina Glacier is exposed for a mile or two, and is seen to rest on unconsolidated gravels and clay. The ice at the bottom of the glacier, owing to the washing out of gravel from beneath, forms a small line of bluffs in the face of the boulder-covered escarpment, at a height of about ten feet above high tide. This is one of the many instances that might be cited where a glacier rests upon loose unconsolidated material which is not perceptibly disturbed by the imposed load."

In one part of the glacier the ice would appear to be nearly at rest, for "the forest covering the greater portion of the lowlands extends up over the moraine-covered bluff of ice, and thence inland on the surface of the glacier for four or five miles. The face of the ice-bluff is so covered with boulders, earth, and vegetation, that it is seldom one has

[1] The altitude of these hills, mentioned above, proves that earth movements on a grand scale have occurred during a geological epoch so near the present that little or no change has taken place in the fauna of the neighbouring sea.

so much as a glimpse of the ice beneath." Beyond this belt of vegetation, which is so dense that nearly a day's hard work was required to cut a trail through it,[1] comes a broad zone of bare moraine, a desolate waste of broken stones and boulders of the same general character as the forest-clad belt, but with less of the finer material and no accumulated humus. Mr. Russell also observed some marginal lakes, corresponding in their formation with the well-known Märjelen See in Switzerland, and mentions the occurrence of "Nunataks" on the ice-field. He also describes some facts which may be helpful in explaining certain ridges, called "kames" or "eskers," which are mentioned in a subsequent chapter. "When the streams from the north reach Malaspina Glacier, they invariably flow into tunnels and disappear from view. The entrances into the tunnels are frequently high arches, and the streams flowing into them carry along great quantities of gravel and sand. . . . The streams flowing from the glacier bring out large quantities of well-rounded sand and gravel, much of which is immediately deposited in alluvial cones. . . . The streams issuing from the ice are overloaded, and besides, on emerging, frequently receive large quantities of coarse débris from the adjacent moraine-covered ice-cliff. The streams at once deposit the coarser portion of this,

[1] It consists chiefly of alders, growing to a height of 20 to 30 feet, but towards the exterior spruce-firs occasionally attain a diameter of about three feet.

thus building up their channels and obstructing the outlets of the tunnels. The blocking of the tunnels must cause the subglacial streams to lose force and deposit sand and gravel on the bottom of their channels; this causes the water to flow at higher levels, and coming in contact with the roof of the tunnels, enlarges them upwards; this in turn gives room for additional deposits within the ice, as the alluvial cones at the extremities of the tunnels grow in height. In this way narrow ridges of gravel and sand, having perhaps some stratification due to periodic variations in the volume of the streams owing to seasonal changes, may be formed within the ice. When the glacier melts, the gravel ridges contained in it will be exposed at the surface, and as the supporting walls melt away, the gravel at the top of the ridge will slide down so as to give the deposit a pseudo-anticlinal structure. Ridges of gravel deposited in tunnels beneath the moraine-covered portion of the Malaspina Glacier would have boulders dropped upon them as the ice melts, but where the glacier is free from surface débris there would be no angular material left upon the ridges when the ice finally disappeared. . . . The process of deposition, as is sketched above, pertains especially to stagnant ice-sheets of the Malaspina type which are melting away. In an advancing glacier it is evident that the conditions would be different, and subglacial erosion might take place instead of subglacial deposition."

PART II

TRACES OF THE GLACIAL EPOCH

CHAPTER I

LAKE BASINS AND THEIR RELATION TO GLACIERS—THE PARALLEL ROADS OF GLENROY—ESKERS, ETC.

In the preceding chapters we have endeavoured to collect the principal facts relating to ice and its work. The one gives a sketch of the scenery, and describes the deposits in a land which was formerly overspread with ice. For this Switzerland was selected rather than Scandinavia, because its situation permits us to attribute all its deposits, dating from the Glacial Epoch, to the action of land-ice; for it is generally admitted that, since this epoch began, the whole country has been above the sea. The other chapter attempts to depict regions where a Glacial Epoch now prevails, in which also the work of ice, both on land and by sea, can be studied. Greenland, for this purpose, is exceptionally instructive, because it must reproduce very closely the conditions prevalent in the north-western part of the European continent during the Glacial Epoch, and thus must throw light on certain difficult problems which the latter presents. These we pass on to consider. The first—the vexed

question of the part played by large masses of ice in the excavation of lake basins—has a less direct connection with Greenland, and will be discussed in the present chapter, together with other collateral subjects. The second practically amounts to this—How far can the work and deposits of land-ice be distinguished from those which are more immediately due to floating ice? This question can be most conveniently discussed in connection with the history of the British Isles during the Glacial Epoch, and is thus reserved for the next chapter. Each question at the present time is a battle-field in geology, and though it will be convenient to consider the two apart, the one cannot be wholly separated from the other. In either case we shall do our best to state the facts which have been ascertained, to give the rival interpretations, and to indicate the points in each which appear to be strong or weak, when they are regarded in the light of results established by the study of cases where either there can be no controversy or the differences of opinion, comparatively speaking, are but slight.

In the year 1862 the late Sir A. Ramsay[1] sought to prove that the lakes in and about the chain of the Alps had been excavated by the ancient glaciers. The following is a brief summary of his paper, which, whether the conclusions of the distinguished author be ultimately accepted or not, did great service

[1] *Quart. Jour. Geol. Soc.* xviii. (1862), p. 185.

in clearing away misconceptions by which the inquiry previously had been much obscured:—

(1.) None of these lakes lie in simple synclinal troughs, that is to say, in synclines the axis of which has a general correspondence with the longer diameter of the lake basin. As the author says: "The lake hollows in the Alps are encircled by rocks, the strikes, dips, and contortions of which often exhibit denudation on an immense scale; and in no case is it possible to affirm, here we have a synclinal hollow of which the original uppermost beds remain." Neither do they lie in any area of special subsidence, such as might be produced by the dissolving and removal of underlying masses of rock. Though this occasionally might be a cause, the number of adjacent dimples in the earth's crust, which this hypothesis not seldom would demand, and the fact that the basins often lie among rocks which are practically insoluble, is fatal to it as one of general application.

(2.) The Alpine lakes cannot be hollows eroded by the rivers which still pass through them. "Running water may scoop out a sloping valley or gorge, but (excepting little swallow-holes) it cannot form and deepen profound hollows, so as to leave a rocky barrier all round."

(3.) The Alpine lakes do not lie in lines of gaping fracture. This idea, which found much favour with some of the older geologists, is disposed of conclusively by showing that even the deepest and narrowest of

these lakes, when drawn on a true scale, bears no resemblance whatever to a fissure. Since the date of Sir A. Ramsay's paper many sections of the beds of lakes have been published, founded on more accurate and much more numerous observations than existed in 1862, and these have placed the accuracy of his reasoning in this respect beyond question.

These hypotheses, as the most probable, having been considered and dismissed, the author shows that the Alpine lakes lie in the paths of the glaciers or ice-sheets which once radiated from the mountains; that they are "broad or deep according to the size of the glaciers that flowed through the valleys in which they lie, this general result being modified according to the nature of the rock and the form of the ground over which the glacier passed." In some cases the presence of a lake may be determined by a sudden increase in the thickness of the ice owing to a confluence of glaciers in a restricted area, such as a rather deep and steep-sided valley, or by some other cause the exact nature of which cannot now be recognised. Sir A. Ramsay also pointed out that in all regions of the Northern Hemisphere which unquestionably have been subjected to great glaciation, such as many parts of Scandinavia, Finland, the Outer Hebrides, the Highlands of Scotland, and districts of North America, "the whole country is covered with a prodigious number of lakes." Accordingly, all other explanations fail-

ing, he concludes that one agency alone remains, "that of ice, which from the vast size of the glaciers . . . must have exercised a powerful erosive agency. It required a solid body, grinding steadily and powerfully in direct and heavy contact with and across the rocks, to scoop out deep hollows" in situations such as have been already mentioned.

These arguments were subsequently re-stated by Dr. A. R. Wallace,[1] who urges an additional one, which is thus expressed:—"If we look at the valley lakes of our own country and of Switzerland, the first thing that strikes us is their great length and their situation, usually at the lower end of the valley, where it emerges from the higher mountains into comparatively low country." Basins of glacial erosion do not invariably occur in mountain valleys, because they require a combination of favourable circumstances, but three criteria may be formulated by which such basins are distinguished from ordinary valleys:—(1.) They "never present those peculiarities of contour which are not infrequent in mountain valleys, and never exhibit either submerged ravines or those jutting promontories which are so common a feature in hilly districts." (2.) "Alpine lake-bottoms, whether large or small, frequently consist of two or more basins, a feature which could not occur in lakes due to submergence, unless there were two or more points of flexure for each depression,—

[1] *Fortnightly Review*, November and December 1893.

a thing highly improbable even in the larger lakes, and almost impossible in the smaller." (3.) The contour lines in most river valleys run up the tributaries for a certain distance, so that, on taking them at heights of "two or three or five hundred feet," these would "form a series of notches or loops of greater or less depth at every tributary stream with its entering valley or deeply cut ravine;" while in the lakes of glaciated districts the water never makes inlets up the inflowing streams, but "all of them, without exception, form an even junction with the lake margin, just as they would do if entering a river."

Opponents of the glacial-erosion hypothesis reply that no one of the last three statements is strictly accurate, and that some of the Alpine lakes not only exhibit a complicated form, but also occur in situations where the excavatory force of the ice-stream must have been very slight, while they are wanting in those where it ought to have been more potent. The Lake of Lucerne and that of Lugano are curiously complicated in shape, and appear to occupy parts of the beds of valleys confluent from rather opposite quarters. Supposing, however, that the former has been scooped out by glaciers, what explanation can be given of the Küssnacht arm, which runs out to the north-east at an angle of about 60° with the main body of the lake? Granted that the ice contingent from the direction of the Brünig Pass may have pro-

duced some deflection in the Reuss Glacier (which would be the chief agent in the work of excavation, and must have taken the same path as the river), it hardly could have forced that glacier to send out an offshoot which actually bends back on its general course. In connection with this, another difficulty arises as to the origin of the Lake of Zug, 650 feet in depth. Did the aforesaid offshoot descend from the top of the "Hollow Lane," and thus acquire, on a slope little more than 200 feet vertical, a sufficient plunging force; or was the work done by an arm extruded from the old Reuss Glacier, which first scooped out the Lake of Lowertz? The former lake, which is deep in proportion to its size, seems to be situated just at the place where the ice might be expected to be least active. Yet a third difficulty is presented by the Lake of Lucerne. East of the part just mentioned it is almost divided into two by the mountainous promontory of the Bürgenstock. This must have seriously obstructed the path of the main ice-stream, and ought to have either forced it aside to the west in the direction of Stanz, where it would have been encountered by the glacier from the Engelberg valley, or obliged it to struggle through a comparatively narrow gateway, on the portals of which an agent so potent should have produced a much more marked impression than is to be discovered. In the case of the Lake of Lugano, it is urged that, while the surrounding hill ranges are high enough to

prevent the great ice-streams of the main valleys[1] from descending in any force into the area now occupied by the lake, they are not sufficiently lofty to originate an important glacier system.

As to the inference that the comparatively regular outlines of the Alpine lakes indicate that they have been excavated by ice, opponents reply that Dr. Wallace has forgotten the fact that this effect is produced by the subsequent deposit of débris. Alluvial fans are formed only under certain circumstances at the junction of a tributary stream with the main river, while, in the case of a lake, the sudden arrest of the affluent water at once forms a delta, and obliterates the irregularities of the shore. Draw your contour lines, they say, slightly higher up the hillside, often but a few yards above the present level of the lakes, and along ground over which the ice-stream must have passed, and the same class of outlines will be found in these as in all other valleys. Further, while the shapes of the lakes are admitted, partly for the reasons just given, to be generally somewhat regular, the rule has many exceptions; as, for instance, the great fork in Como, the headland of Sermione in Garda, the irregular shapes of the Lac d'Aiguebelette and the Lac de Breney, the islands in Maggiore and Iseo, and in Annecy we find not only the headland and island at Duingt, but also the vast "pot-hole" at Bourbioz, and the submerged steep-sided hill near the

[1] Those now traversed by the Ticino and the Adda.

Crêt-de-Châtillon.[1] Sometimes the actual channel of a river can be traced for a certain distance along the beds of the lakes, and their contours under water are very closely related to those of the mountain-side above, while a "single sheet of M. Delebecque's Atlas shows what varied forms these lakes can assume, and the work as a whole presents to us a number of basins, some lying in the path of the great ice-streams, others quite out of it, others again in regions which only can have been invaded very incompletely or for a short time by a glacier, and of these certain lie transverse to its path and parallel with protecting ridges."[2] The difficulty of the two or more basins which are often noticed in the bed of a lake is thus answered. Commonly these variations in the depth only amount to a few yards vertical, and are very probably due, as M. Delebecque has pointed out, to the irregular deposit of morainic material on the present lake-bed; while in the case of the larger lakes, the occurrence of a slight undulation in a general line of flexure would not be surprising.

The comparative frequency of lakes in mountain regions which once supported large glaciers is admitted to be a coincidence of some importance, but attention is called to the fact that the rule has many excep-

[1] For the less familiar instances—the lakes of the French Jura or Alps—consult the most interesting work by M. Delebecque, *Atlas des Lacs Français*, in which the subaqueous contours of the lakes are carefully mapped, in accordance with an elaborate system of soundings.

[2] *Contemporary Review*, 1894, July, p. 115.

tions. Of two important valleys in the Alps, one has a lake and the other has not. In one mountain chain lakes are comparatively frequent, in another very rare, if not altogether wanting—as, for instance, in the Himalayas, the Caucasus, and the Pyrenees. In the last-named chain, the glaciers, though not equal to those of the Alps, were far from insignificant; greater, at any rate, than the ice-streams of the Jura, which, whether they were of local origin or straggling offshoots from the main Alpine masses, must have excavated lake basins, if the hypothesis under discussion be correct. The Pyrenean glaciers were occasionally between forty and fifty miles long; they came down to the lowlands in situations very favourable to a process of digging; yet there are no lakes. Again, Nicaragua and Titicaca, and the lakes in San Domingo and Porto Rico, in Celebes and Tasmania, bear much resemblance to some of the lakes of the Alpine region; yet these cannot be attributed to the action of ice, for Agassiz's dream of a vast glacier in the valley of the Amazon has been long dispelled; and though Tasmania, as will be seen, once had its glaciers, they were mostly, if not wholly, in a different part of the island from the lakes.

But, in addition to these objections on points of detail, issue is joined on the main question, viz., whether a glacier is an excavatory agent of any real importance. Admitting that, under certain favourable circumstances, such as at the foot of a steep

descent, or above an impediment to an onward flow, like a narrowing of the valley, a glacier may be able to excavate a shallow basin—admitting that ice, in other words, may produce the tarns in corries and the lakelets in sundry hill regions, the opponents of Ramsay and Wallace deny that it is in general an *erosive* agent of any importance. Its effects in grinding rock surfaces, and in producing large amounts of mud and coarser débris, to which appeal is constantly made, prove merely its *abrasive* force. A glacier in its passage makes the rough places smooth, and changes angles into curves, but it fails to obliterate the broader outlines which are characteristic of the erosive action of running water; for in the higher parts of many Alpine valleys, where the ice lingered longest, though every rock is smoothed and scored almost down to the level of the torrent, the V-like section characteristic of fluviatile erosion is conspicuous, instead of the U-shaped trough which should be the result of ice. Lower down these valleys, the ice has swept round and over projecting crags of no great importance, without having planed them away; it has overflowed beds of boulders and comparatively loose débris; while in the glens already mentioned, though they are often several leagues in length, tarns are comparatively rare, even if every bit of level meadow be claimed as a filled-up basin. The glacier appears often to have been impotent as an excavatory agent during the greater part of its course, and reserved itself for one

final effort at or near its point of emergence from the mountains. Even in Greenland, where the great glaciers, during some temporary shrinking, have exposed the rock beneath, this is not excavated, but is only brought to a level surface by the giant ice-rasp.[1]

Those geologists who are unable to accept Sir A. Ramsay's hypothesis attribute the larger lake basins to differential movements of the earth's crust. A mountain range or chain, they say, consists primarily of a group of parallel folds in this crust. Suppose such a region to have been sculptured by the usual agencies into hills and valleys; the latter, as carrying off the drainage, will run more or less athwart the lines of folding. Suppose next, that, at a very late epoch in the history of the chain, a new set of earth movements be initiated along the old lines, though not necessarily with the same intensity or effect in every part. The result will be that the floor of a valley will here rise above and there sink below its former level: the line which once shelved gently outwards will be bent into a curve; the ascending part will dam up the river; the descending part (higher up the valley) will form a basin in which a lake will accumulate. The advocates of this hypothesis cite, in confirmation of it, the region of the Great Lakes in North America. These lakes, as stated in the last chapter, lie in the path of the vanished ice-sheet. They appear to be true rock

[1] E. Whymper, "Scrambles among the Alps," chap. vi.

basins. They vary in shape, and the forms of some, if only their scale were reduced, would find parallels among the Alpine lakes; indeed, at one time there was a disposition to claim them as the work of ice. But by Professor J. W. Spencer,[1] and other geologists of Canada and the United States, these lakes are shown to be part of a great river system—the upper valleys of the present St. Lawrence—which has been depressed more rapidly than the lower part.[2] Before the lakes were formed the drainage of the country differed in several important details from that which now exists. Under the waters of Michigan the heads of two valleys are buried, the northern of which communicated with the area of Lake Huron along the present line of junction, while the southern took an eastward course across the great promontory of Michigan State to Saginaw Bay on the same lake. The united waters of these rivers ultimately passed from the southern end of Georgian Bay along a channel (now buried) to the northern side of the valley occupied by Ontario. At this time the neighbourhood of Detroit was a watershed. The Erie region at first probably drained southward, and only at a later date in the direction of Ontario.

Again, not only were the Great Lakes produced by

[1] *Quart. Jour. Geol. Soc.*, xlvi. (1890), p. 523.

[2] Probably the whole of this part of America is at a lower level than it was when the valley of the St. Lawrence was first defined.

differential movements of the earth's crust, after its leading outlines of hills and valleys had been sculptured, but also these movements have been subsequently continued. Around the shore of the lakes, at levels extending sometimes as much as 1700 feet above the present surface of the waters, raised beaches may be found overlying, and thus more recent than, the newest till. These of late years have been carefully traced and measured. They form more than one group, and thus indicate different levels of the water; but, what is of great interest and importance, the beaches belonging to one and the same epoch of formation do not lie at a uniform height above the present lake surface. To take a single instance,[1] "The most important raised beach of the Ontario basin is the 'Iroquois.' At the western end of the lake it now rests at 363 feet above the sea, but rises slightly to the east, and still more towards the north, until at four miles east of Watertown it is 730 feet above the sea. Still farther north-eastward, near Fine, on the borders of the Adirondack Wilderness, it reaches an elevation of 972 feet above the sea. . . . At the western end of the lake the uplift is scarcely two feet in a mile in the direction of N. 28° E. At and beyond the north-eastern end of the lake the uplift is found to have increased to five feet in a mile, and in the region of farthest observation to somewhat more in a north-eastward direction.

[1] Professor J. W. Spencer, *loc. cit.*, p. 530.

Thus in the deformed water-level I have already measured a barrier of about 609 feet raised up at the outlet of the lake. . . . South-east of Georgian Bay the average measured warping is four feet per mile, in mean direction of N. 20° E. This will account for a portion of the barrier closing the Georgian outlet of Lake Huron. The more elevated beaches in the region of Lake Huron record a still greater change of level. At the outlet of Lake Erie, Mr. Gilbert and myself find a differential uplift of about two feet per mile, and this is sufficient to account for the recently formed basin of Lake Erie." As the outcome of his observations in this region, Professor Spencer is led to the following conclusions:—"The valleys of the great lakes here studied are the result of the erosion of the land surfaces by the ancient St. Lawrence (named Laurentian) River and its tributaries, during a long period of continental elevation, until the streams had reached their base-lines of erosion, and the meteoric agents had broadened the valleys. This condition was at the maximum just before the Pleistocene period. The closing of portions of the old Laurentian valley into water basins occurred during and particularly at the close of the Pleistocene period, owing, in part, to drift filling some portions of the original valley, but more especially to terrestrial warpings of the earth's crust." It is to movements analogous to those which have formed the Great Lakes of America that geologists

appeal who are sceptical as to the great excavatory power which has been claimed for ice.

To conclude: the controversy is far from being decided, but perhaps its present state may be not unfairly summed up as follows:—The frequent coincidence of lake basins and glaciated regions is favourable to the one hypothesis, while the direct evidence generally is adverse to the excavatory action of ice, except under very special circumstances, and in some cases it accords better with the other hypothesis.

Few natural phenomena which are connected with the Glacial Epoch have been more fruitful in controversy than the Parallel Roads of Glenroy.[1] The sides of this valley, a tributary of Glen Spean, slope in general towards its bed rather steeply and equably. The roads, three in number, may be compared to terraces on the hillsides, and are so singularly uniform in outline and level as to resemble at first sight the work of man rather than of nature. They are, on an average, about twenty yards in width, and they shelve very gently outwards, being slightly steeper in the narrower than in the broader parts. They run continuously, except where they are cut through by lateral ravines or glens, or, locally, where either bare rock appears or the slope of the hill becomes very much less than usual. The materials of the roads

[1] The most important papers of recent date are by Professor Prestwich, *Phil. Trans. Roy. Soc.*, 1879, Part II. p. 663, and Mr. T. F. Jamieson, *Quart. Jour. Geol. Soc.*, xlviii. (1892), p. 5. In these references to most of the earlier literature will be found.

are angular or very slightly rounded fragments of the rocks which occur on the slopes above them. The height of the uppermost is about 1150 feet above sea-level; of the second, about 1065 feet; and of the third, about 855 feet. Besides these there are some other terraces of a more ordinary character near the entrance to Glen Roy, the height of which is about 400 feet, that of the Bridge of Roy being about 310 feet. Similar terraces, though much less perfectly developed, occur in one or two neighbouring valleys; the best, a single one, being in Glen Gluoy, at an average height of 1165 feet, and there are "shelves" in Glen Spean itself at greater elevations. While it is agreed that these roads are beaches, there has been much controversy as to both the exact mode in which they have been made and how the water has been brought to their levels. In regard to the former point, it is, we believe, now generally admitted that Sir J. Lubbock has propounded the correct explanation, which also is independent of any hypothesis about the cause to which the level of the water was due. The slopes of the hills descending to Glen Roy, as a rule, are covered with an unusually thick mantle of débris. Assuming the glen to have been occupied by a sheet of water to just over the level of the highest road, the fretting of the waves would tend to cut a cliff at the base of the mountain slope above; but as the materials of this were incoherent, débris would be constantly slipping down, which would be

spread out under water, and rest against the slope below at its natural angle of repose, 35°, or rather more. Whenever the water was kept for a long time at the same level, a considerable part of the coating of the hillside would be transferred by this process from above to below the surface, and the new material would form a beach, which for a certain distance would shelve very gently from the land, and then would descend steeply towards the bottom of the glen.

Suppose, now, that the level of the water was rather rapidly lowered, till it again paused for a long time in a like position with regard to the second road. As before, the newly deposited débris would be attacked, and the outer portion of it transferred from above to beneath the water, so as to form another terrace. Were this process continued long enough, the first road might be destroyed; but if we suppose the water, before this work has been accomplished, to sink to the level of the third road, that would be formed in like manner at the expense of the second; and when the water finally departed, three roads would remain, much as they now may be seen.

The cause which brought the water to these levels is still a matter of dispute. By some authorities they are considered to have been formed by the sea when the land stood at a lower level than at present; the highest being the oldest, and the second and third marking pauses in the process of upheaval. By other authorities they are attributed to fresh water, and are

supposed to have been formed on the shores of lakes, which were held up by glaciers during some part of the Ice Age.

The advocates of the marine origin call attention to the fact that terraces of a rather similar kind occur at lower levels in other parts of Scotland, especially on the western coast. On that of Norway two lines of sea-marks are common, appearing as terraces in loose materials and as grooves or clifflets on the ice-worn rocks. On the coast of Peru they are not uncommon, occurring near Valparaiso up to a height of 1295 feet above the sea, and in the valley of the Rio de Santa Cruz, at successive stages, to nearly the same elevation. Geologists of this school appeal also to the shells in the gravels at Moel Tryfaen, at Gloppa, and at other localities, which they maintain can be accounted for only by a submergence during a part of the Glacial Epoch, and they urge that the phenomena of Glen Roy accord very well with what they suppose to have been the history of that epoch, viz.: (1) an extensive glaciation when the level of the land was rather higher than at present; (2) a depression during which most of the ice disappeared, followed by a return nearly to the old level, with pauses during which the roads were made; (3) an increase of the ice, but to nothing like its former extent, resulting only in the development of local glaciers in some of the valleys.

At first sight this explanation seems to be the most

simple and probable, but it is not without difficulties, of which the following are the most important:—

(1.) If these beaches have been formed by the sea, it is difficult to understand why they do not occur more generally in the neighbouring valleys and in other parts of Scotland. To this it is answered that there is a beach in Glen Gluoy, and some traces are found, though at different levels, in Glen Spean and elsewhere. But terraces of this kind, as the Norway coast shows, are always rather unusual. They are only formed under exceptional conditions, and are accordingly local in occurrence.

(2.) The level of the terraces in Glen Gluoy ought to agree with that of the upper terraces in Glen Roy (since the heads of the glens are only a few hundred yards apart), instead of being some fifteen feet higher, while in Glen Roy itself the level of each terrace should be rather less uniform; for it is improbable that the whole valley—about ten miles long—would be uplifted to the same amount. To this it is answered, that in other parts of Scotland, terraces, admitted to be of marine origin, alter their level but slowly, and the facts above stated merely require that the land in rising should be tilted slightly upwards towards the north, while it remained nearly at the same level towards the west. It is admitted, in short, that the conditions would have to be a little exceptional, but denied that they are impossible.[1]

[1] On this matter authorities are not in accord as to the facts. Mr. T. F. Jamieson denies that there is any real variation in the level of a

(3.) No marine organism has been detected among the materials of the roads; nothing, indeed, but some fresh-water diatoms. Had these beaches been formed by the sea, the shells of some marine molluscs, if only in fragments, ought to have been discovered. It is answered that this objection might be urged with equal force in regard to many of the terraces in Scotland and Norway, the marine origin of which is not to be disputed; for these, as a rule, are unfossiliferous, the remains of marine organisms being rare and local. It is very probable that if the ice-cap melted as the land sank, the valleys invaded by the sea would be but slowly colonised by a marine fauna, for the water would be cold and brackish, and the conditions of life less favourable than on the more open coasts.[1] As numerous streams descend the flanks of the valley, the occasional presence of fresh-water diatoms is not surprising, especially when it is considered that these organisms often may be transported for considerable distances by the wind.

The "glacier-lake" hypothesis has been advanced in two distinct forms. One, the more usual, asserts that the streams from the upland district around Glen

road, and attributes the appearance of it to the difficulties of obtaining corresponding points for measurement. In any case. it is not more than a few feet.

[1] So far as I remember, molluscs or other marine organisms (excluding seaweed), though plentiful among the islands of the Norwegian coast, were not generally common between tide-marks and along the shores of the fjords. See in reference to this question, "Life, Letters, and Journals of Sir C. Lyell," vol. ii. p. 46.

Roy were blocked at some lower point by a glacier or glaciers, and that the ice-dam was strong enough to hold up the water, and convert Glen Roy into a lake; the other, that the valley was occupied by a glacier, but that the streams were held back by an uprising of the ice in the lower part of Glen Roy itself, this "welling up" being probably due to the crowding together in a narrow space of the glaciers issuing from sundry valleys.

In regard to the former hypothesis, opinions have been very diverse as to the position of the great ice-dam. In this matter conjecture finds a fairly open field; for there are no very conspicuous moraines in the valley of the Spean below the Bridge of Roy, to which appeal can be made in fixing its position in one place more than another. With some forms of the hypothesis it also becomes necessary, since the "cols" at the heads of some of the arms of Glen Roy are below the level of the highest road, to assume the existence of local glaciers, so situated as to "plug" these openings for a time, and to prevent any lateral leakage from the lake. The apparently rapid lowering of the waters obviously could be caused by a giving way either of these barriers or of the main one. The latest view (which appears to be the one most in favour at the present time) thus explains the situation.[1] The principal ice-field in Scotland in the

[1] Condensed or quoted from paper by Mr. T. F. Jamieson. *Quart. Jour. Geol. Soc.*, xlviii. (1892), p. 5.

Glacial Epoch extended southward from Ben Nevis over the Moor of Rannoch to the head of Loch Lomond; the second one, northward from Glen Arkaig to Loch Shin. "Seeing that these two ice-fields met and coalesced at the western entrance of the Caledonian Canal, it is evident there must have been a great congestion in that quarter, for here was a narrow passage with heavy streams of ice coming into it from the glens on both sides all the way down to the head of Loch Linnhe. The quantity of ice that filled the Great Glen and the mouth of Glen Spean was so great that it eventually overflowed the passes leading eastward into the valleys of the Nairn and the Spey, notwithstanding that many of these passes are actually higher than those to the westward, which lead out to the Atlantic. This western ice broke over Strath Errick in great force; it filled Glen Gluoy, and flowed out at the top of it; it likewise occupied Glen Roy, and went out to the eastward over the pass at the head of that glen." Then the ice began to shrink, as the temperature rose, towards the conclusion of the Glacial Epoch. "The 'col' or watershed at the head of the Spey became sufficiently open to admit of water passing out, and as soon as the ice melted out of the top of Glen Roy a lake would take its place, discharging itself over this 'col.' Such a lake at first might be superficial—that is to say, resting on the surface of the decaying glacier. Gradually the ice receded farther and farther down Glen Roy,

and became reduced in height; but the surface of the lake, being determined by its outlet, would stand at the uppermost line until the icy barrier melted back as far as the mouth of Glen Glaster. As soon as the water gained admission to this side glen, it would escape over the 'col' at the head of it (if there was no obstruction in the way), and as that 'col' is eighty feet below the one at Lochan Spey, the lake would then sink to the level of the middle line, which corresponds with the Glen Glaster 'col.' There it stood for a time, until the ice which yet occupied the lower end of Glen Roy shrank back still farther—far enough to allow of the water communicating with Glen Spean, which it would probably do first over the hollow between Meal Derry and Craig Dhu, near Bohinia. When this event happened, the lake would spread into Glen Spean, and, if there was no obstruction to the eastward, would drop to the level of the lowest line, which corresponds with the escapement at Makoul" (p. 10).

Lakes held up by ice-dams undoubtedly exist. The famous lake formed in the upper part of the Dranse valley by the Giétroz Glacier was an instance, though it had not a long existence. The well-known Märjelen See, by the side of which is a terrace rather like one of these roads, has a more permanent character; but, like the two or three other examples supplied by the Alps, it is small in size, being hardly three-quarters of a mile long. Similar lakes exist on a larger scale

near the margin of the ice-sheet in the more southern part of Greenland, and such probably would be competent, under favourable circumstances, to produce the roads. But opponents have asked—and the question seems difficult to answer—how it was that the upper part of Glen Roy could be free from ice when the rest of the Highlands was able to generate a mass sufficient to block either the lower part or the mouth of the valley, and hold up so great a body of water. Here, they say, the analogy of the Märjelen See does not hold, notwithstanding other points of resemblance, because the 'col' at its head is only a little more than 7700 feet above the sea, or considerably below the level at which glaciers now form in Switzerland, while the Great Aletsch Glacier is supplied from peaks and snowfields which rise from three to six thousand feet higher than the little glen which is occupied by the lake. Mr. Jamieson, however, has proposed a way of escaping from this difficulty. He points out that at the present day the rainfall over the district on either side of the entrance to the Great Glen (the feeding-ground of the ice-sheets named above) is exceptionally heavy (80 inches and upwards[1]), while over the district to the east of this (in which Glen Roy lies) it

[1] On the north-west side of the Caledonian Canal (central part of Ross-shire, Inverness-shire, and the north of Argyle) the rainfall sometimes rises above 100, and south-east of the Canal it is somewhat higher, amounting in Glencoe to full 127 inches. *Nature*, 1894, October 18.

declines in that direction from 80 to 40 inches. Thus, in the Glacial Epoch, the snowfall on the former district would be nearly double that on the latter, and great glaciers might be produced in the one, while they would be small or even wanting in the other. This no doubt is true to a certain extent, but the dissentients submit that the argument does not really overcome the difficulty. The change from a precipitation amounting to 80 or 100 inches on the western district to one of half the amount on the eastern, is not sudden, but gradual, even if it be somewhat rapid, so that the rainfall on the hills above Glen Roy can hardly be less than 60 inches, and may be rather greater. Moreover, the difference in elevation between the two districts is not very great. Though Ben Nevis rises to a height of 4406 feet, it considerably overtops its neighbours, while much of the upland around Glen Roy lies rather above the 2000-foot contour line. Thus, the average height of the two districts can hardly differ by so much as 1000 feet, which corresponds with a disparity in mean temperature amounting to not more than 4° F. Hence, even if allowance be made for the heavier snowfall, the glaciers of the western region would not be large when the head of Glen Roy was free from ice; and if the former became enormous, then Glen Roy itself would be occupied by ice-streams from the surrounding uplands, and its glaciers might even descend to the valley of the Spean.

Professor Prestwich's hypothesis[1] avoids this difficulty. He supposes that, at the end of the time of most severe cold,[2] "the old ice-sheet of Scotland became covered with pools and lakes, which would go on filling until the water reached the lip of the basin, when the surplus waters would escape along the natural lines of drainage, either on or beneath the ice, to some lower levels; but when, owing to exceptional circumstances, such as those which prevailed in the Spean and Roy valleys, the ice had been heaped up in larger masses so as to raise high the water-level, then these lakes, dammed back pending the removal of the barriers, made their temporary outflow over any 'cols' lying at a lower level than the barriers, and leading into adjacent valleys free from such blockages. So while every mountain-side was contributing its rills and rivulets to innumerable temporary pools and tarns on the melting ice, their waters were, in such instances as those presented by the Lochaber valleys, retained and formed lakes ultimately extending the length and depth of the glens"[3] (p. 695).

[1] *Phil. Trans. Roy. Soc.*, 1879, Part II. p. 663.

[2] He considers the roads to have been formed at the end of the first or coldest part of the Glacial Epoch, while Mr. Jamieson assigns them to a rather late stage in that epoch.

[3] Professor Prestwich thinks that the "roads" were formed, not by the erosive action of the waves of these lakes, but by the slipping of the loose materials on the hillsides, owing to the sudden removal of support when one of the barriers gave way and the waters escaped. This is almost a necessary part of the hypothesis, for in such lakes the erosive action of waves would be very slight.

Lakes of this kind undoubtedly exist. There are two in the upper part of the Gorner Glacier, just at the foot of Monte Rosa; but even the larger of them is not more than about a couple of hundred yards across in any direction. Professor Prestwich quotes some instances from the great glaciers in the Himalayas; but even these are comparatively small, the largest mentioned being not a third of a mile long; while, though both the Himalayas and Greenland are better known than when his paper was written, no lake of this kind has been discovered which is in any way comparable in size with that which the hypothesis demands. It is also difficult to see how a glacier, under the circumstances alleged, could be sufficiently solid to retain so large a sheet of water as would be required to form these roads. Passing over other difficulties of a less general character, it may suffice to say that the hypothesis, notwithstanding its ingenuity, and the fact that it avoids some serious objections to which the other mode of attributing a fresh-water origin to the roads is exposed, does not appear to have met with general favour.

To conclude: the difficulty of the almost unique occurrence of the roads is common in reality to all the explanations; each has to postulate something exceptional in the conditions of the district. The principal difficulties in the way of the marine origin are two in number. One, that the roads require a submergence during the Glacial Epoch amounting to

more than 1150 feet. The possibility of this opens a wide question, not only in regard to terrestrial physics, but also as to the interpretation of the glacial deposits in the British Isles. This question will be noticed in a later chapter. If it can be proved that a submergence to more than the above amount actually took place on the southern side of the Border, there would be nothing startling in its effects extending to Western Scotland. If, however, the deposits in question testify to elevation rather than to depression, then the objections to the marine hypothesis become almost insuperable. The other difficulty, that of the absence of any marine organism, both in the roads and at any other like elevation in Scotland, though it may be explained, as has been mentioned above, is undoubtedly a grave one. The main objections to the fresh-water hypothesis (apart from the question of a submergence) turn upon the difficulty of accounting for the existence of a mass of ice huge enough to act as a dam for such a body of water, under circumstances which would allow of Glen Roy, with parts of some neighbouring valleys, being free from ice.[1] Hence, as there are difficulties on all sides, the history of the Parallel Roads of Glen Roy is likely to remain for the present among the controversial questions of geology.

Much has been written about certain ridges of

[1] The gravity of this will be better appreciated after a study of some of the later chapters of this book.

FIG. 10.—The Kames of Maine and South-Eastern New Hampshire. (Stone.)

débris more or less water-worn, which are variously called Kames, Eskers, or Åsar (pronounced Osar);[1] and though they are generally admitted to be among the phenomena of a Glacial Epoch, the question of their origin is hardly yet settled. These kames are ridges, sometimes sharp, sometimes comparatively flat at the top, which run across the country, following generally the direction of the main streams, though not always exactly taking the same course, or keeping to the lowest ground. Occasionally they may be traced continuously for many miles,[2] "running like great artificial ramparts across the country;" sometimes they terminate abruptly. In external aspect they often present a general resemblance to a lateral moraine, but differ from it internally in being composed of materials more or less water-worn, and in exhibiting a stratification which often is most distinct. Very commonly the beds are arranged with a certain relation to the form of the mass, and are seen in a transverse section to slope outwards roughly parallel with its sides, or even to form a series, though an irregular one, of concentric arches. A group of them will be described more fully in connection with the glacial deposits of Ireland, in the

[1] The first name, of Scotch origin, means "comb." "Ås," in Swedish, is a beam, and is used sometimes for a hill-ridge, "åsar" being the plural. Full accounts of them are given in Professor J. Geikie's "Great Ice Age," chaps. xiv. and xxxi., and in Dr. Wright's "Ice Age of North America," chap. xiv.

[2] Erdmann, quoted by Professor J. Geikie, gives instances of åsar in Sweden varying in length from 125 to over 200 miles.

lowlands of which country, as of Scotland, they are commoner than in England. They have been recognised in Northern Germany, in the neighbourhood of the Baltic; they are abundant also in parts of Scandinavia, Finland, and Russia, and of North America. To quote from Professor J. Geikie's excellent description,[1] they are—at any rate in the Baltic coast-lands—of later date than the youngest boulder clay of that region, upon which they sometimes rest, but oftener perhaps on solid rock. They rise abruptly to a

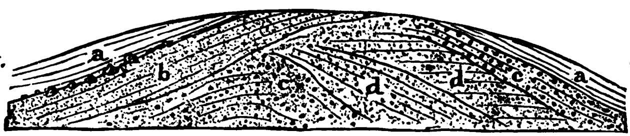


FIG. 11.—Section of Kame near Dover, New Hampshire. Length, 300 feet; height, 40 feet; base, about 40 feet above the Cocheco River, or 75 feet above the sea. *a, a,* grey clay; *b,* fine sand; *c, c,* coarse gravel containing pebbles from six inches to one foot and a half in diameter; *d, d,* fine gravel. (Upham.)

height of from 50 to 100 feet above the average surface of the ground. "Sometimes, however, they reach as much as 180 feet, while now and again they sink down to 30 or 20 feet, or even disappear altogether below newer deposits. Their sides have an inclination of from 15° to 20°, but occasionally as much as 25° or even 30°, and the two declivities very rarely slope at the same angle. Often beginning

[1] *Loc. cit.*, chap. xxxi.

in the interior of the country, the åsar follow the valleys down to the low coast-land, across which they pass as well-defined ridges out to sea, after a course of not infrequently more than a hundred English miles. In the mode of their distribution they show a striking resemblance to river-courses. . . . At greater heights than 300 feet above the sea these remarkable ridges are, as a general rule, confined to the valleys, but at lower levels they seem to be tolerably independent of the present configuration of the ground. They are met with at all levels up to and above 1000 feet. The materials of which they are composed may consist either of coarse shingle, or of pebbly gravel, or of sand, or it may be made up of all three. In some parts of a ridge shingle and gravel predominate, in others sand is the principal ingredient. In one place the stratification may be distinct, in other places obscure."

As a rule, according to Professor J. Geikie, the stones in the gravel of these kames or åsar are well rounded and water-worn, though exceptions to this are occasionally found, the deposits being unstratified and earthy, and the stones subangular, or even angular; the one type of deposit being associated with the other in a way that shows them to be connected. Erratics are rarely embedded in the gravels, but are not unfrequently found dotted over the tops and slopes of the hillocks, as if they had been dropped upon the surface.

There has been a tendency of late to distinguish between the use of the terms kame and esker, and to refer the one to groups of irregular hillocks, the course of which is transverse to the direction of a valley or of the main drainage line of a country, and the other to the somewhat more regular mounds which run more nearly parallel with the path of the water. It is possible that the distinction may prove to be of service, though between the two types no hard and fast line can be drawn.

Of these curious mounds, whether they be thus separated or not, various explanations have been offered. Some geologists have supposed them to be marine deposits, heaped upon the bed of a rather shallow sea by the action of currents, probably tidal. Professor Hull,[1] for instance, offers this explanation for the very remarkable series which, as will be mentioned later on, occurs in Ireland. "While the land was still being elevated, and fresh tracts were emerging into day, or were being brought within the reach of surface waters, it may easily be imagined that the tidal and other currents, being forced to oscillate within narrow channels bounded by the ridges of the unsubmerged land, would act with considerable effect on the soft materials of the drift, both in sweeping them away and in piling them up along tortuous lines in the form of embankments. . . . Mr. Kinahan observes that the eskers

[1] Physical Geology and Geography of Ireland, Part I. chap. v.

in the strip of country lying between Dublin and Galway form a compound bar, consisting of well-defined ridges or 'bar-eskers,' and in other places of 'shoal-eskers.' The 'bar-eskers,' from Galway to Tullamore, or thereabouts, are usually on ground under the 250-feet contour line, and from Tullamore to Dublin on ground under the 300-feet contour; while the 'shoal-eskers' towards the west are on ground between the 250-feet and the 300-feet contour, and towards the east between the 300-feet and 400-feet contours."

But the hypothesis of a marine origin presents serious difficulties. Apart from the fact that, according to the principal authorities, no shells or other organisms belonging to the sea have been found among their materials, it is very difficult to understand how currents in the sea could have piled up these singular ridges, and have produced the peculiar structures mentioned above. In the latter respect, and in situation, the kames or eskers are very different from ordinary beaches; they may indeed be compared to some extent with such banks as the noted Chesil Bank, which extends from Portland to Abbotsbury, or to the "bars" of sand and gravel, like those at Torcross and Budleigh Salterton in Devonshire, or at the Looe Pool in Cornwall. All these, however, are exceptional in character, the Chesil Bank being most probably only a beach of shore-shingle, which has been subsequently isolated, and the others being bars,

which were formed at the confluence of a river with the sea, when the level of the land was a little lower than it is at the present time. It is difficult to understand how conditions such as those to which these mounds are due could act generally over a large area of submerged land, or why the zones of deposit, produced by the conflict of currents, should so often run parallel with the present drainage system of the country.

To the majority of geologists at the present day these ridges appear to have a connection with land-ice. By some they are regarded as the relics of ancient river-beds, excavated either in till or in glacial mud after the disappearance of the ice-sheet. By others they are thought to mark the sites of tunnels underneath the ice, *i.e.*, the paths of subglacial rivers. By others, again, these rivers are supposed to have flowed, not underneath, but upon, the sheet of ice. When this was travelling over a lowland, crevasses would be, in their opinion, very rare, so that the water from the melting surface, instead of plunging down a "moulin," as on Alpine glaciers, would carve out for itself a valley system on the great field of ice. "As this melts, the morainic material contained in it is released, and tends to find its way from all the valley slopes into the streams, the bottoms of which become in this way paved with sand, grit, and rock débris. This material, carried forward by the tumultuous waters, suffers more or less attrition, and sand and gravel are formed. . . . Thus layer after layer accu-

mulates in the beds of the rivers as the ice-sheet melts, until finally the ice disappears, and the old river-courses then show themselves as ridges rising prominently above the surrounding low ground." The hypothesis is ingenious, but, as a preliminary condition, the existence of an ice-sheet must be taken for granted in many places where its presence is still a matter of dispute, and doubts may be entertained whether this method of accumulation is probable, and whether deposits thus formed would not be thrown into great disorder during the final melting of the ice. It is also by no means certain that débris could gather in any large quantity on the surface of the ice until the latter had been so greatly diminished in volume that it could no longer extend very far into the lowlands. Because, when an ice-sheet is very large, but little rock can rise above it, at any rate in a country without lofty mountains. In districts such as those which have been mentioned, the formation of great ice-sheets seems only to be possible when the hills are completely buried, as in the interior of Greenland. If that be so, any débris that might be detached must travel, not upon the surface of the ice, but beneath it, or at any rate in its lowest layers. Hence, if these ridges really are the leavings of ice-sheets, the hypothesis of subglacial rivers seems to offer fewer difficulties. But they are also present in this hypothesis, for, besides the main question of the presence of an ice-sheet, the shape and structure of

the mound is hardly what might have been expected. On the whole, rivers, swollen by melting ice or snow, seem the more probable cause; but it is still open to discussion whether kames and eskers are to be regarded as monuments of subglacial torrents, or as marking

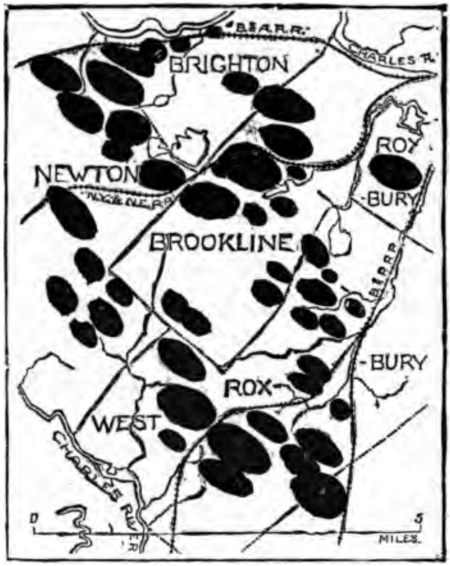


FIG. 12.—Drumlins in the vicinity of Boston. (Davis.)

the paths of streams which, in the latter part of the Glacial Epoch, cut their way through expanses of soft and fine material which subsequently has been removed.

In conclusion, yet another kind of deposit may be mentioned, which offers difficulties somewhat similar

to the last named. This is a drumlin, a "name now used to designate the class of glacial accumulations which Professor Hitchcock originally called 'lenticular hills.'" Dr. Wright, whose words we have just quoted, states[1] that they abound in the neighbourhood of Boston, and largely give character to the scenery of the three north-eastern counties of

FIG. 13.—Drumlins in Goffstown, N.H. (Hitchcock.)

Massachusetts. They have been noticed in Scotland by Professor J. Geikie, and in Ireland by Mr. Maxwell Close.

According to a description given by Mr. Warren Upham, "these hills vary in size from a few hundred feet to a mile in length, with usually half to two-thirds as great width. Their height, corresponding to their area, varies from 25 to 200

[1] "The Ice Age in North America," chap. xi.

feet. But whatever may be their size and height, they are singularly alike in outline and form, usually having steep sides, with gently sloping, rounded tops, and presenting a very smooth and regular contour. . . . The trend, or direction of the longer axis, of these lenticular hills is nearly the same for all of them comprised within any limited area, and is approximately like the course of the striæ or glacial furrows marked upon the neighbouring ledges." According to Dr. Wright, these hills resemble in structure the lower portions of the till. They are only imperfectly if at all stratified, and are formed of very compact clay filled with foreign and finely striated stones. They occur at various altitudes above sea-level in America, even up to 1500 feet on the tract between the Merrimack and Connecticut Rivers.

Drumlins are attributed to the action of ice by most geologists who have discussed their origin, though some think them to have been shaped by the sea. By the majority, however, they are believed to have been formed above water. Some suppose them to mark the site of ancient "moulins," on a scale adequate to the vanished ice-sheet, when so much débris was carried down by the plunging water that it accumulated in huge heaps at the bottom, which afterwards, when the course of the stream had been diverted by the opening of new crevasses, were modified in shape by the pressure and sculpture of the moving ice. Some regard these drumlins as

morainic masses, which, when the ice-sheet has subsequently advanced, have met with a somewhat similar treatment, so that they represent the original contour of the till after the first ice-sheet had melted away. Others again compare drumlins with the sandbanks in rivers, and look upon them as masses of unstratified drift, slowly and locally accumulated under the irregularly moving ice-sheet, in places where more material was brought than could be carried away.

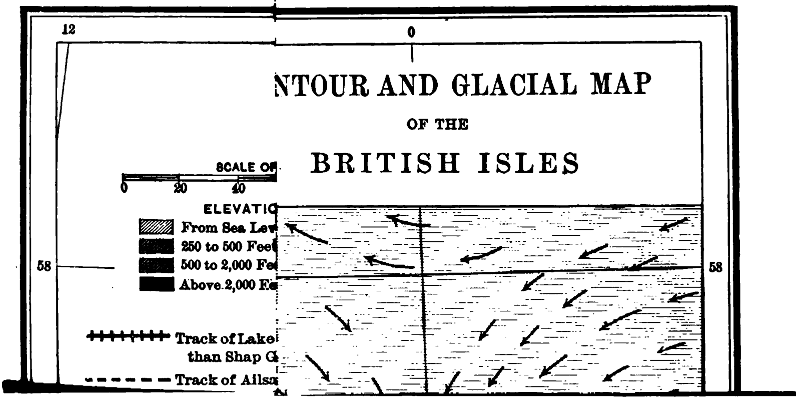
To the objection, that these hypotheses are incompatible with the erosive action generally attributed to ice, their advocates reply that this action was confined to mountain regions, where the valleys were steep, or to broken hilly tracts, where the ice must have flowed with comparative rapidity, but irregularly; while in the open lowlands and broad valleys, where it would advance with diminished but more equable motion, it would be powerless either to abrade or to erode, and thus accumulation might take place beneath it. This principle is not improbable, but if it be adopted, it will be found to create difficulties in regard to the hypothesis which attributes the larger lake basins to the excavatory action of ice; for these often lie in valleys where the slope of the ground is slight, and in districts where large masses of till have accumulated.[1]

[1] For instance, according to Dr. Wallace (*Fortnightly Review*), the ice only begins to excavate at the foot of the mountains; that is to say, where the slope becomes comparatively gentle.

CHAPTER II

ICE-WORK IN GREAT BRITAIN AND IRELAND—THE DEPOSITS AND THEIR SIGNIFICANCE

OVER no small part of the lowlands in Britain, as far south as the northern margin of the Thames valley, deposits occur which are generally admitted to be indicative of a temperature considerably lower than at the present time, even if they are not the direct products of land-ice. Somewhat similar deposits reappear in a limited area on the Sussex coast. Contemporary beds very likely occur in the intervening districts; but as they nowhere exhibit characteristics distinctly glacial, all correlation can be only conjectural. Some traces of ice action probably remain in the south-west of England, but here also the evidence is less conclusive than in the central and northern regions. Among the glacial deposits of the lowlands, the most characteristic is a boulder clay. This contains numerous pieces of rock, ranging in form from rounded to angular, but as a rule more or less subangular, embedded in clay, sometimes loamy or sandy, but generally stiff and tenacious. Those of smaller size commonly are more or less worn, and are often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smoothed and striated by the action of ice; the larger, however, like the boulders in a moraine, are commonly unscratched, and little or not at all worn. The clay varies in colour and character in different parts of the country; it usually bears some resemblance to the argillaceous strata which outcrop either in the immediate neighbourhood or at some distance to the north. The smaller fragments also, as a rule, have travelled from the same quarter; but the larger boulders, especially in the more western districts, seem to occur in fairly well-defined "streams," which, however, as will be seen, do not always follow the same rule of dispersion. With this clay, from which the stones may locally disappear, masses of stratified gravel and sand are intercalated. These sometimes are mere lenticular streaks, limited in extent both horizontally and vertically; at others, they attain a thickness of several yards, and may be traced over an area many square miles in extent. They are not confined to any one horizon, but, at any rate on the lower ground, they are more abundant towards the middle part of the mass. Thus, on both the east and west sides of England, it has been found generally possible to divide the glacier deposits into an Upper and Lower Boulder Clay, separated by the so-called Middle Glacial Sands and Gravels. But in the interior and on the higher ground, one boulder clay only can be found, sometimes overlying sands and gravels, which, however, are very often absent. In other places the sands and

gravels dominate over the clay, or the two may be interbanded in lenticular streaks or masses. The areas in which a Lower Boulder Clay can be recognised are rather limited in extent and marginal in position, and this deposit is said not to occur at heights greater than 500 feet above sea-level, while the Sands and Gravels, with the Upper Boulder Clay, range up to nearly 1400 feet, and possibly even higher. These, however, are exceptional cases: it is not often that boulder clay occurs more than about 800 feet above the sea.

The glacial deposits occasionally admit of a further subdivision, and the accuracy of this tripartite arrangement is disputed by some observers of experience. Certainly it cannot be pressed too far; the more arenaceous division may be sometimes absent, and the two clays may coalesce. In many places, however, there is a general truth in the statement that a mass of sand and gravel is frequently found to underlie a boulder clay, which can be traced over no small part of England, and that the former, in the neighbourhood of the coast, not seldom covers another mass of boulder clay. We must, however, remember that these deposits are not arranged with anything like the regularity of those belonging to considerably earlier geological epochs. Even in the same pit, and within an area of half an acre, the observer, on successive visits, may find that the sections indicate considerable variations. Nothing more than a general truth can be claimed for any classification, and it must not be forgotten that glacial

conditions would persist in a northern district for some time after they had ceased to affect one farther to the south, so that a boulder clay in the former might be the contemporary of a sand in the latter. These deposits also commonly lie like a mantle upon the pre-existing land surface, and thus one and the same bed may be found at very different elevations.

A complete description of the variations of the glacial deposits at different localities in Britain would be impossible within the limits of this volume. We must content ourselves with a few sections which may serve as samples of the rest, referring the reader for further details to the excellent summary given by Mr. H. B. Woodward,[1] and then proceed to consider the explanations which have been offered of these difficult and interesting deposits.

We leave aside for the moment the more mountainous districts, such as the higher parts of Wales, the Lake District, and Scotland, because less difference of opinion exists in regard to these, all geologists admitting that, during the larger part of the Glacial Epoch, they were occupied, if not by an ice-sheet,

[1] "Geology of England and Wales" (2nd edit.), where many references to original memoirs are given. Much information also is to be found in the "Memoirs of the Geological Survey," though occasionally the facts of Nature and the opinions of the author are not divided by a sufficiently sharp line. There is hardly a volume of the *Quarterly Journal of the Geological Society* and of the *Geological Magazine* for many years past which does not contain at least one paper of some importance, and the "Reports of the Erratic Blocks Committee of the British Association" are full of valuable information.

at least by glaciers, which sometimes attained to a very considerable size. We restrict ourselves at present to the lowlands, and in so doing shall find it more convenient to notice separately the great streams of erratics, which, as already mentioned, radiate from certain definite centres. Facts shall be described first, and the interpretations proposed be considered afterwards.

The Norfolk coast may be chosen as the first example, for it yields to none in interest, and is classic ground in glacial geology. The cliffs for some miles on either side of Cromer exhibit a magnificent series of sections, which chiefly expose deposits of Glacial age. The oldest rock visible is the uppermost part of the Chalk,[1] the surface of which occasionally rises a few feet above high-water mark, but is more commonly below it. Lying on this thin patches of a gravelly fossiliferous deposit — the Weybourn Crag (Upper Pliocene)—are sometimes found. Then comes the group of deposits containing the well-known "Forest Bed," the highest of them being a pale yellowish-grey sand, called, from the occasional presence of that fossil, the *Leda myalis* bed. The thickness of the last-named is commonly about a dozen feet, and that of the group as a whole varies from 20 to 30 feet. This sand is succeeded by the so-called "Cromer Till," which, however, if

[1] This is, generally speaking, the zone of *Belemnitella mucronata*.

FIG. 15.—Typical section of Till in Seattle, Washington State, about 200 feet above Puget Sound. This is on the height between the Sound and Lake Washington.

we observe Professor J. Geikie's distinction,[1] is a true boulder clay; over this comes the Contorted Drift, a remarkable mass of stratified sand and gravel, occasionally clayey, containing erratics which often are of a huge size. The Contorted Drift is followed by other sands and gravels, representative of the Mid-Glacial series; and lastly comes another boulder clay, which, in the neighbourhood of Cromer, is not seen on the coast, though it may be found inland, extending for a great distance. Later than this are gravels, coarse and fine, at various elevations and of different dates. These, however, though often indicative of climatal conditions very different from such as are now prevalent, hardly come within the scope of this book.

The Lower Boulder Clay or "Cromer Till" consists of a more or less sandy clay, in colour dull bluish-grey to brownish, containing numerous rock fragments.[2] Most of these are small, varying from a

[1] He suggests ("The Great Ice Age," chap. xv.) that the term "till" should be restricted to deposits containing erratics from the same district, or virtually from the same valley system. Hence, applying the word in the latter sense, all those boulder deposits in the Swiss lowlands, which were described in the first chapter, we might call "tills." When the rocks have come from diverse sources, often from afar, he would name the deposit "boulder clay." According to this definition, the Cromer deposit is not a true "till." Many authors, however, do not distinguish the terms. As Professor Geikie himself states, this cannot always be done; at the same time, when possible, it is useful, as calling attention to distinctions which may prove to be important; so it will be retained, as far as may be, in these pages.

[2] In some places it is separated into two divisions by a bed of

couple of inches in diameter downwards. They generally consist of flint and chalk, the former more or less angular, the latter more or less rounded and often striated. Pebbles and larger fragments of older rocks, which occur *in situ* at various localities farther north, are also present, though in less abundance. Among these are various Jurassic and Carboniferous rocks, basalts and felstones, granite, gneiss and schists. The crystalline materials have probably come from the north-east of England and from Scotland, but a few have been referred to Scandinavia.[1] Slight indications of stratification are not infrequently perceptible in this boulder clay, which is generally divided from the *Leda myalis* bed by a sharply defined but fairly level surface, though an approach to interlamination is sometimes perceptible.[2]

The passage of this Lower Boulder Clay (Cromer Till) into the so-called Contorted Drift is often obscured by the singular disturbances exhibited by the latter; but the two, in several places, are perfectly interlaminated, bands of sand and of boulder clay

stratified sands and clays. See "Memoirs of the Geological Survey: The Country around Cromer," chap. xi.

[1] Among them a peculiar porphyritic felstone, which is called *Rhomben-porphyr*, and an elæolite-syenite. So far as is known, these occur *in situ* not on the west coast of Norway, but on the south-east coast, facing the Skager Rack.

[2] In certain sections a thin deposit intervenes, indicating an old land (or fresh-water) surface, and containing various Arctic plants. Farther away the boulder clay (Cromer Till) is underlain by gravels, but the above description is true for some miles on either side of Cromer.

(containing tiny pebbles of chalk and flint) being beautifully interstratified for a thickness of a few feet, the layers of each varying from two or three inches downwards. The Contorted Drift consists of materials showing every gradation from a gravel—sometimes coarse—to a sand like that on a sea-shore or to clay, which, in places, are distinctly and evenly stratified.

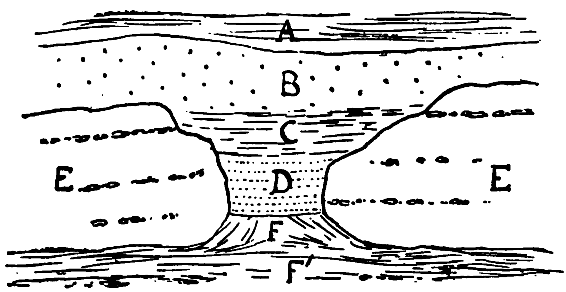


FIG. 16.—Erratics in Glacial Drift: from the cliffs west of Cromer.

A. Some 20 feet of laminated sand, with slips above. *B*. Strong grey clay. *C*. Laminated clay. *D*. Laminated sand. *E*. Mass of chalk with flints, nearly 6 yards long. *E′*. *Id.*, rather more than 8 yards long. *F*. Talus. *F′*. Shore.

But the beds often exhibit the most extraordinary twists and contortions; and the confusion is increased by the not infrequent presence of large included rock masses, in addition to the boulders already named as occurring in the "till." These consist of chalk (with lines of flint), of reconstituted chalk, and even of gravel. They are frequently 7 or 8 yards in length,

and they are stated to reach as much as 150 or 180 yards. In thickness, however, they seldom exceed about 4 yards. These gigantic erratics, so far as I have observed, do not occur in the underlying boulder clay, though occasionally they may be seen almost in contact with its upper surface. These two deposits make up the Lower Glacial series in Norfolk. The "Mid-Glacial Sands," as a rule, are free from important erratics, and more uniformly bedded than the Contorted Drift. The Upper Boulder Clays, which are best studied inland, and may be traced through the adjoining counties into other parts of England, contain abundant fragments, generally representative of rocks occurring farther north. These, usually, are rather small, boulders exceeding a yard in diameter being rare, though occasionally, as will be presently mentioned, very large masses have been found.

The Yorkshire coasts[1] often display fine sections; but the correlation of the deposits with those described above is by no means easy, and they exhibit considerable variations in detail. Of the more northern type, the cliffs between Filey and Filey Brigg may serve as an example. Here a clayey mass, often full a hundred feet in thickness, overlies the Jurassic rocks. The clay varies from brownish to reddish, this latter tint being more marked in the upper part. It is probably

[1] The boulder clays inland extend to about 800 feet above sea-level, but they are more prevalent in the valleys than on the limestone uplands of the north-eastern part of the county. Woodward, "Geology of England and Wales," p. 497.

due to the presence of material obtained from the Keuper Marls farther north. Near the Brigg, the base for perhaps four feet above the Jurassic rocks is rather sandy, and has a stratified aspect, and the browner clay is separated from the redder by a sandy band from three to four yards thick, distinctly stratified, into which each seems to pass rather gradually. The clays also often present slight indications of stratification, and a more sandy band sometimes occurs in the upper one. Both contain fragments, but these are more numerous in the lower bed. They are in all conditions, from rounded to angular, but most of them vary from angular to subangular,[1] well-rounded stones being in the minority. Generally they are less than an inch in diameter, but larger specimens are not rare. These more commonly run up to six inches, but occasionally are twelve inches, or even more.[2] They consist of coal, shales (Liassic certainly, and perhaps Carboniferous), various limestones (Carboniferous, Permian, and Jurassic), many sandstones and grits (Mesozoic and Palæozoic), basalts, greenstones, and numerous felstones, often apparently from Scotland and the Cheviots, with other more distinctly crystalline rocks, such as granites, gneiss, and schists. Most of these last suggest a Scotch origin, but Shapfell granite is found, and some, as stated above, have been claimed

[1] Some are striated, but good examples of this marking are not common.

[2] Boulders two feet or more in diameter occur, but they are rare.

as Scandinavian. In other words, the bulk of the fragments indicate a drift from a quarter to the north or north-west. In the upper mass of clay fragments are less numerous, and seem to run smaller, and in both the masses the clay distinctly predominates over the fragments. From Filey Brigg to Speeton Cliff the drifts continue, and the sections exhibit two clays parted by a sandy gravel, which is frequently well stratified, and sometimes is full twenty feet thick. Here also the clays often show signs of stratification.[1]

The coast sections between the chalk cliffs of Speeton and of Flamborough Head, and for a long distance southwards from the latter, again afford fine exposures of the glacial drifts. These have been studied by many observers, one of the fullest and most recent descriptions being that by Mr. G. W. Lamplugh.[2] On either side of Bridlington Quay,[3] a boulder clay, generally of a brownish colour, is the lowest member of the group. Next comes a mass of sand, with laminæ of clay or gravelly streaks, generally well stratified, sometimes false-bedded. This is associated locally with beds of gravel or with seams of boulder clay. In other words, the mass varies much in its

[1] Sometimes the clay appears to be laminated, sometimes it passes locally into sand banded with clay.

[2] *Quart. Jour. Geol. Soc.*, xlvii. (1891), p. 384.

[3] The chalk on the southern side of Flamborough Head terminates in a buried cliff and beach, of which Mr. Lamplugh has given an admirable account. The section was well displayed in 1893, but not in the spring of 1894.

minor details, but sands and gravels dominate. Another boulder clay follows, which, however, is better displayed on the Holderness coast. Here also the lower clay (called by Mr. Lamplugh the "Basement Clay") may be recognised, and we can distinguish in some places at least three masses of boulder clay, separated by beds of sand or gravel, which occasionally suggest the possibility of yet further subdivision. The upper mass of boulder clay, which in Holderness is distinctly reddish in colour, was distinguished by Mr. S. V. Wood, jun., as the Purple Clay.[1] Fragments are less numerous in it than in the Basement Clay.[2] As to the correlation of these deposits with those on the Norfolk coast, different opinions have been held. Mr. Lamplugh considers the "Basement Clay" the equivalent of the "Cromer Till" in the "Lower Glacial Deposits" of that district, and the Purple Clay as nearly on the horizon of the "Chalky" or "Upper Boulder Clay" of East Anglia. Though the lithological differences between these deposits are considerable, there is very much to be said in favour of this view. Many authors have distinguished a Hessle Sand and a Hessle (Boulder) Clay in parts of Yorkshire, and have placed these at a higher level than the Purple Clay; but Mr.

[1] *Quart. Jour. Geol. Soc.*, xxiv. (1868), p. 146.

[2] In the latter, shells, whole and broken, are sometimes not rare, and in it occur patches of sand containing molluscs, the bivalves often having their valves united. These have been called the Bridlington Crag. Mr. Lamplugh is of opinion that these shelly sands were not formed *in situ*, but are of the nature of erratics.

Jukes-Browne has shown,[1] and with this view Mr. Lamplugh concurs, that not only is this subdivision of merely local value, but also the "Hessle" deposits generally are hardly separable from the Purple Clay.

On the other side of the Humber similar sections occur, but are not generally so well displayed; in short, the glacial deposits of North-East England are a group of boulder clays, and of gravels or sands, the former on the whole predominating, and the latter being more persistent towards the middle part. These gravels and sands must have been deposited under water, and they not seldom indicate the action of fairly rapid currents. The boulder clays sometimes show no signs of stratification; at others they have a laminated structure, the included fragments also suggesting a certain regularity of disposition, while now and again distinct interlaminations of more sandy materials occur. In other words, nothing is found irreconcilable with the idea that the clays also were formed under water, while certain phenomena require explanation if the materials were deposited on a land surface which generally was occupied by ice.

Before leaving this subject attention may be directed to a rather remarkable line of hills which crosses the peninsula of Flamborough Head, running from Beacon Hill northward to Sanwick, and then continuing for some miles farther, roughly parallel with and a short distance from the coast, till it sinks into the glacial

[1] *Quart. Jour. Geol. Soc.*, xli. (1885), p. 114.

deposits occupying the Vale of Pickering. The range at first is gently undulating, but it becomes more defi-

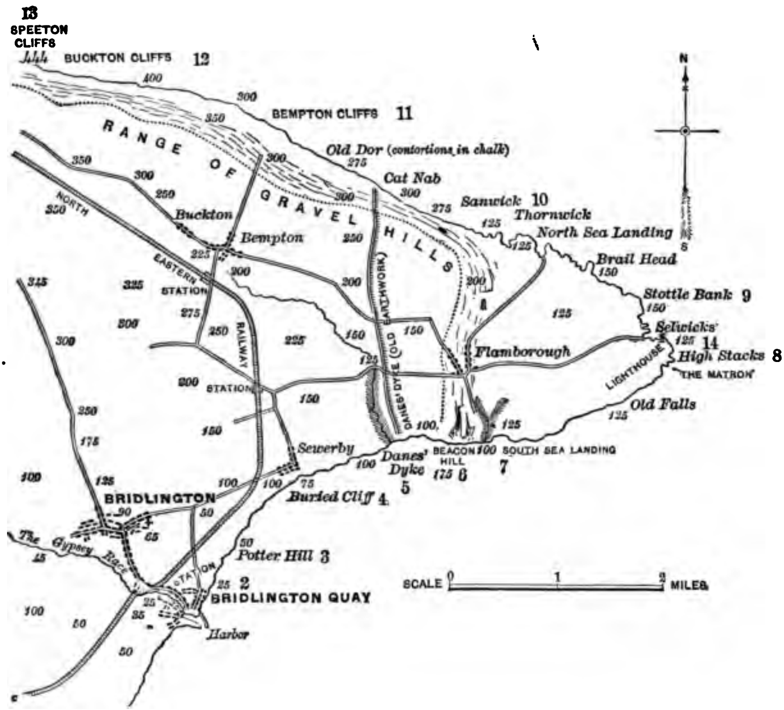


FIG. 17.—Supposed Moraine between Speeton and Flamborough.

nitely ridge-shaped in the neighbourhood of Speeton village. The hills, as is shown in the coast sections, are composed of sands, gravels, and clays; stratified,

doubtless, though somewhat irregularly, and exhibiting often the peculiar structure called "arched bedding."[1] Of late years these hills have been frequently claimed as remnants of the right lateral moraine of a glacier which occupied the bed of the North Sea and trespassed on the Yorkshire coast, but their resemblance externally to a moraine is not striking, and their internal structures are totally different.[2]

The glacial deposits of the north-west of England, as far south as parts of Cheshire and North Wales, admit in some places of a tripartite division, viz., a Lower Boulder Clay, Intermediate Sands and Gravels, and an Upper Boulder Clay. This division, however, as in the eastern counties, cannot always be maintained, and the middle member is sometimes wanting, the one boulder clay shading into the other, so that they can hardly be distinguished. The first, according to Mr. H. B. Woodward's[3] summary, is a "stiff

[1] That is to say, the component layers, though often irregular and lenticular, are arranged in rude symmetry with the outer surface, or at any rate in a series of more or less concentric curves.

[2] Moraine deposits (due to land-ice) are practically unstratified. Traces of stratification may be now and then detected, just as in any talus heap, and probably from the same cause (a slight packing or shifting of the material in process of time); but these are faint, rare, and local, so far as my experience goes, and it is by no means small. Certain cases which have been quoted to prove the contrary from America are not conclusive, because the origin of these deposits is open to question. "Arched bedding" would be a very improbable structure in a moraine. Its cross-section should exhibit (if anything) either a series of inverted Vs broadening from the apex, or groups of bands parallel to one side, the latter being the less improbable.

[3] "Geology of England and Wales," p. 488.

reddish-brown clay, with subordinate beds of laminated loam, seams and pockets of sand, stones and many large boulders. . . . The lowest portion of the accumulation is a blue or bluish-grey stony clay with many scratched boulders." The maximum thickness of the whole deposit is about 120 feet, but it is generally much less. "The Middle Drift consists of fine sands and gravel with subordinate beds of clay and loam, the whole in general distinctly stratified, but frequently contorted;" the maximum thickness (at Kersal Moor on the west of Manchester) being 200 feet. "The Upper Boulder Clay consists of reddish-brown clay, with grey and blue partings, and glaciated stones and boulders. It sometimes contains bands of sand and finely laminated clay," and attains a thickness of about 100 feet as a maximum. But the total thickness of the three deposits, when they occur in the same area, is rarely more than from 150 to 200 feet.[1]

The Cumbrian mountains and the adjacent lofty fells of the Pennine Range obviously have been occupied by glaciers, for among them ice-worn rocks, moraines, and perched blocks are common. During part of the time the glaciers, at any rate in the former district, must have descended very near to, if not below, the present sea-level. Here the older

[1] Foraminifers and ostracods have been found in the two boulder clays, and molluscs in all the deposits (sometimes rather abundantly in the sands), lists of which are given by Mr. W. Shone, *Quart. Jour. Geol. Soc.*, xxxiv. (1878), p. 383.

deposits appear to be a true till; these are followed by stratified sands and gravels, which may be traced up to about 1500 feet above sea-level.[1] They are overlain in places by moraines and other deposits, which indicate a second advance of the glaciers. That there was formerly a great mass of land-ice in this region is universally admitted, but how far it extended beyond the hill district, and whether the sands and gravels were deposited during a time of submergence (and consequent retreat of the ice), or in some other way, are still subjects of dispute.

The mountainous part of North Wales affords similar evidence. As to the Snowdonian district, the former presence of large glaciers is beyond dispute. They must have descended at least to the present sea-level. The lower spurs of the rocky hills on either bank of Llyn Padarn are often ice-worn to the water's edge; perched blocks are poised here and there, and the trail of vanished glaciers may be followed, as Sir A. Ramsay pointed out many years ago, right up the pass of Llanberis. Indeed, the peculiar outlines of the less weathered rocks in parts of Anglesea are suggestive of the action of land-ice, and erratics are abundant. In North Wales also we find sometimes indications of a tripartite division, for in places stratified sands and gravels are both overlain and underlain by a true boulder clay.

[1] Mr. Clifton Ward, *Quart. Jour. Geol. Soc.*, xxix. (1873), p. 422, and xxxi. (1875), p. 152, infers from these deposits that the submergence may have amounted to rather more than 2000 feet (xxix. p. 437).

One section requires a fuller notice, for, as will be seen hereafter, much depends upon its interpretation. This is on Moel Tryfaen, a kind of outwork of the Welsh mountains, which rises steadily, and in parts fairly steeply, from the lowland by the coast to a height of nearly 1400 feet above the sea. Bare crags—a mass of conglomerate—form the summit, but at no great distance below it extensive quarries have been opened in a thick bed of purple slate. This, over a considerable area on either side of a line running E.S.E. of the summit, and in some places within about 50 feet vertically below it, is covered by superficial deposits, the sections of which are being constantly exposed in the process of quarrying. Immediately above the solid slate-rock comes a breccia of the same, which runs from about eighteen inches to nearly a yard in thickness. This is overlain by a bed of sand and pebbly gravel, somewhat irregularly but very distinctly stratified, which evidently lies like a mantle over a considerable area of the rounded shoulder of the hill. Above this a boulder clay is often, but not always, found. It is brownish in colour, containing fragments, generally from the size of a man's head downwards, but occasionally larger; the upper part, varying in thickness from two to four feet, being greyer in colour and comparatively free from stones. The clay occurs in a "pockety" manner, the line of junction, which usually is clearly defined, rising and falling rather

rapidly for three or four feet; the bands in the sandy bed below being often puckered and crumpled, but in some cases clearly bending beneath the clay, as if they had been squeezed down by a pressure from above. The whole is covered by a foot or two of stony earth; the total thickness of the superficial deposits being at most about thirty feet. The sand contains marine shells, commonly more or less broken. In all, about fifty-five species have been described.[1] The pebbles are fairly well rounded, and the deposit resembles one formed in shallow water, like the drift which may be seen on the lower ground nearer the sea. Boulders larger than those mentioned above are not common in the clay, but erratics of greater size may be seen lying at rather lower levels on the slope of the hill, where also well-rolled pebbles are scattered about, sometimes rather abundantly. The erratics for the most part certainly are Welsh rocks; some, however, seem to have come from Anglesea, and a few pebbles of Cumbrian and Scotch rocks have been found.[2] Fragments of a felstone containing a rare and peculiar variety of hornblende (*Riebeckite*) are not

[1] Eleven species are Arctic. Most of the molluscs are littoral in habit, the rest such as live in from ten to twenty fathoms of water (J. Gwyn Jeffreys, *Quart. Jour. Geol. Soc.*, xxxvi. (1880), p. 355). Of some species more than one variety was present, and five other marine organisms were represented.

[2] Occasional pebbles and boulders of northern rocks (granite from Eskdale, Criffel, &c.) have been found by various observers in the boulder clays and gravels of North Wales. See D. Mackintosh, *Geol. Mag.*, 1872, p. 18.

infrequent.[1] A mass of this forms the conspicuous hill called Mynydd Mawr, the summit of which rises to the E.S.E. about a mile and a half away.

Shells, as well as other marine organisms, are found sometimes, as already stated, in the British boulder clays, though they are generally very rare. In the sands, however, they are less infrequent, Moel Tryfaen being by no means the only locality. They occur (at a height of 1200 feet) to the east of Macclesfield, where the beds are about 33 feet thick, and to the north of that town at a height of 500 feet and upwards. These beds reach a thickness of 100 feet, and at Congleton are overlain by boulder clay. "Shells have been found at Upton and near Tarporley in Cheshire, at Preston (350 feet high), Leylands (Worden Hall Pits), and Blackpool in Lancashire. . . . Shells have also been found in the Drift at Petton in Shropshire, near Crewe, at Lilleshall Abbey, north of Shiffnal, and at Strethill, near Buildwas station, and other places in the Severn Valley between Bridgenorth and Shrewsbury. In Shropshire these shell-bearing sands and gravels are about 30 feet thick, and rest on blue (boulder) clay. At Ironbridge the thickness of the Drift is upwards of 200 feet."[2] The heights of these

[1] Riebeckite occurs in the rock of Ailsa Craig, and fragments of this rock are said to have been found on Moel Tryfaen. This is not impossible; but most of the specimens on the upper part of Moel Tryfaen (which are rather abundant) are the rock of Mynydd Mawr—at least so far as I know the two rocks. Obviously Ailsa Craig is too small a place to have furnished numerous specimens to such a distant locality.

[2] H. B. Woodward, "Geology of England and Wales," p. 492.

deposits above sea-level are from about 150 to over 500 feet. In the pits near Wellington a reddish boulder clay may be seen covering the stratified sands.

But the most remarkable inland instance, a discovery comparatively recent, is at Gloppa, near Oswestry.[1] This locality is at a distance of about thirty miles in a straight line from the nearest part of the sea, the bed of sand ranging from 900 to 1160 feet above sea-level, and the shells being found up to a height of 1120 feet. The thickness of the deposit was proved to be more than 60 feet, but it probably does not exceed 100 feet. The mass is composed of shingle, sand, and loam, with occasional bands of clay. The bulk of the gravel "consists of rounded and subangular stones, the larger stones being angular and subangular. They are in a general way similar to the boulders of the Lower Boulder Clay of Cheshire, as described by the late D. Mackintosh. The bulk of the stones may be set down as Silurian grit and argillite, then felspathic trap rocks, greenstone, granites similar to those of Ennerdale (?), Eskdale, and Criffel, &c., syenite, felsites, Carboniferous limestone, Millstone grit, and vein-quartz. Some Coal Measure shales and sandstones and Permian and Triassic sandstones have been noticed, also a few Chalk flints, and a trace of

Several localities in Shropshire and Worcestershire are mentioned in "The Glacial Geology of Great Britain and Ireland," by the late Professor Carvill Lewis.

[1] Described by Mr. Nicholson, *Quart. Jour. Geol. Soc.*, xlviii. (1892), p. 86.

Liassic shale." Large boulders are numerous, consisting of limestone, sandstone, various granites and syenites, slates, greenstones, porphyritic trap, &c., the boulders and larger pebbles being commonly striated, and many polished. The deposit is not associated with any true boulder clay, the nearest mass of that in the immediate neighbourhood being at a level of 700 feet. The shells are not confined to any one part of the deposit, though they are more abundant in its lower half, and in the fine shingle and gravel. "Their condition varies much. Thus there are many fragments much broken, rolled, and striated, some very fragmentary, but the bulk are in fairly good condition, and entire single valves of *Astarte*, *Mactra*, *Tellina*, &c., are common. A perfect specimen of *Fusus antiquus*, three inches long, was found, and the univalve shells are often well preserved." Above seventy species of molluscs have been determined, with some fragments of cirripeds and a boring sponge. The first agree generally with those discovered at Moel Tryfaen, and exhibit not only the same intermingling of northern and southern forms with those still characteristic of the neighbouring seas, but also a similar variation as to the depth which they frequent.[1]

[1] Valuable summaries of the fauna (mollusca, ostracoda, and foraminifera) of the Boulder Clay and Middle Drift of Lancashire and Cheshire, and of that from Moel Tryfaen, will be found in a paper by Mr. W. Shone, *Quart. Jour. Geol. Soc.*, xxxiv. (1878), p. 383. The following statement gives the number of species of mollusca from the Boulder Clay and the Drift:—*Boulder Clay:* Newton (Upper), 56; Liverpool (Upper and Lower), 44; Dawpool (Lower), 35. *Middle Sands*

In the Midland counties, using the term in a rather extended sense, a tripartite division of the glacial deposits is seldom possible. Frequently boulder clay is the sole representative, sometimes it is underlain by sands and gravels, sometimes the latter only occur. Both attain to a considerable height above sea-level, being occasionally found up to seven or eight hundred feet, but, as the land itself but rarely reaches this elevation, they are generally lower. The boulder clay, which is the more widely spread deposit, mantles over the undulations of the ground, and seems to some extent moulded on the pre-existent physical contours, though it often becomes rather thin, and is sometimes wanting on the uplands and increases in the valleys. It attains a thickness of 160 feet at Old North Road Station in Cambridgeshire, and at least 218 feet in the north of Essex, where it doubtless fills up an old river valley.[1] These, however, are exceptional cases; perhaps from 20 to 40 feet is a fair average thickness. As an example of its character in the more central part of England, we may take the neighbourhood of Narborough in

and Gravels: Upton, 23; Macclesfield, 48; Leylands, 44; Blackpool, 22. From Shropshire, the gravels at Lilleshall give twenty-one species; those at Buildwas, thirty-three; with some other marine organisms in each case.

[1] Mr. W. Whitaker, *Quart. Jour. Geol. Soc.*, xlvi. (1890), p. 337. This thickness, however, is exceeded at the north end of the Isle of Man, at the Point of Ayre, where the Glacial Drift (boulder gravels, sands and clays) has been proved by boring to be 298 feet, and neighbouring hills suggest that 150 feet more should be added. Prof. W. B. Dawkins, *Trans. Manchester Geol. Soc.*, Part xxi. vol. xxii.

Leicestershire, in which good sections are often exposed in the process of quarrying. Here the clay[1] commonly is a bluish-grey colour, but occasionally it becomes reddish; it contains pebbles of chalk,[2] subangular to round, flint, generally in rather angular fragments, septaria, bits of shale and fragments of limestones from the Jurassic formation, some of them containing fossils of the Lias; occasionally also pebbles of quartz and quartzite (probably from the Trias), pieces of chert, and other Carboniferous rocks. These fragments, except where it is specified above, commonly vary from subangular to angular in form: they run rather small, the more angular being rarely as much as a foot in diameter, and the pebbles not often bigger than a duck's egg.

Occasionally, however, very large erratics have been discovered in the boulder clay, as, for instance, at Sywell in Northamptonshire, Ridlington in Rutlandshire, and Stukely in Huntingdonshire. To the south of Grantham, in a cutting near Great Ponton on the Great Northern Railway, an irregular mass of Jurassic rock (Lincolnshire Limestone) was found, which measured 430 feet in length and 30 feet in greatest thickness. Also at Roslyn Hill, close to Ely,

[1] It rests sometimes on the Red Keuper Marl, which is the prevalent rock of the country, sometimes on the outcropping masses of ancient crystalline rock.

[2] I have not found any which exhibit the peculiar flatness characteristic of those from the Chalk in the Flamborough district of Yorkshire.

a mass of chalk some 400 yards in length formerly existed, which of late years has been quarried away. To the base of this a seam of the well-known Cambridge Greensand and a little Gault still adhered, so probably it had been transported for a comparatively short distance.

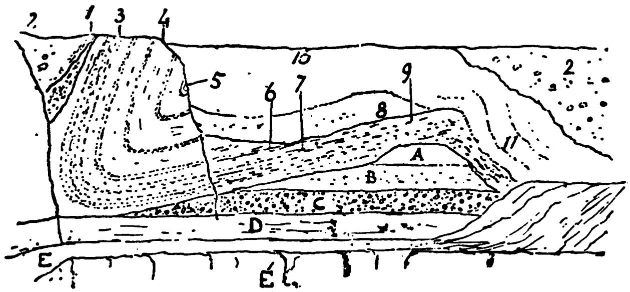


FIG. 18.—Section in Mr. Green's Pit, N.E. of Sudbury.

1. Sandy stuff, sticking on face of boulder clay. 2. Boulder clay. 3. Variable banded sand and fine gravel. 4. Mostly sand, but with indications of bedding. 5. Slightly gravelly sand. 6. Sand. 7. Banded sand. 8. Coarse gravel. 9. Sand. 10. All the part left blank seems to be disturbed by old excavations. 11. White sand.

A. Red sand. *B*. Variable sand and gravel. *C*. White sand. *D*. Sand (Thanet). *E*. Chalk (top). *E'*. Chalk (pit).

In East Anglia the boulder clay caps the plateau of Suffolk, its surface sometimes being quite 300 feet above sea-level. Here, as, for instance, about Cockfield,[1] its thickness is often full 80 feet over a considerable area, and it contains lenticular beds of sand and gravel, which must be sometimes exten-

[1] E. Hill, *Quart. Jour. Geol. Soc.*, xlvii. (1891), p. 585.

sive, as they are large enough to feed wells. Pits in the neighbourhood of Sudbury afford interesting sections of boulder clay overlying bedded sands and gravels. One of them[1] for some time exhibited the deposits shown in Fig. 18. The chalk is covered by a stratum of Thanet Sand (Lowest Eocene), often with a band of green-coated flints at the base. It is generally about two feet thick, and is occasionally overlain by a reddish clay. On this in one place lies Red Crag (Pliocene), consisting of sands and gravels, somewhat irregularly bedded, which forms a kind of ridge, being obviously a remnant left by some process of denudation. This is buried beneath boulder clay, which in the neighbourhood of the Crag passes into interstratified sandy and loamy beds. These are strangely contorted, like the drift already mentioned on the Norfolk coast, the beds in one part being bent into a form something like the letter C. The Crag, however, which is only half a yard or so away from one end of this curve, together with the underlying Thanet Sand, shows no sign of disturbance.

The coast of Suffolk, between Great Yarmouth and Southwold, exhibits good sections of the Glacial deposits. A comparison of these with those already described in Norfolk indicates the variability of the group, and a further comparison with the Yorkshire coast sections suggests that sands and gravels are

[1] First described by Mr. J. E. Marr, *Geol. Mag.*, 1887, p. 262. It was still visible in 1892.

apt to become more abundant towards the south. The highest member, excluding the Plateau Gravels, which are occasionally visible, is the Upper or Chalky Boulder Clay, though this often has been much reduced in thickness, if not entirely removed, by denudation. It is (when unweathered) a dark slate-coloured or blackish clay (probably largely derived from the Kimmeridge Clay), containing small fragments of chalk, which frequently are so abundant as to give it a speckled aspect, pebbles of the same, large and small, often well rounded, pebbles and angular fragments of flint, similarly variable in size, with pieces of Jurassic and other rocks,[1] usually not more than about two feet in diameter, and, as a rule, not nearly so much. Beneath this boulder clay comes generally the Mid-Glacial sands and gravels, which often are about 30 feet in thickness, but occasionally more, about 70 feet being a maximum. On the coast, the sand dominates, and the pebbles (mostly flint) seldom exceed the size of a hen's egg. The deposit is commonly well stratified, and not seldom exhibits false-bedding. Below this is a loam with stones, commonly rounded and rather small (mostly flint), which is considered to represent the Lower Glacial Beds of Cromer. It is sometimes absent, and is generally under 21 feet in thickness. This deposit in some places, especially on the northern side of the district,

[1] Felstones and crystalline rock appear to be less common than in Norfolk, and much less than in Yorkshire.

rests upon a clay (with more or less sand), at the top of which a number of rootlets often may be seen—probably a trace of an old land surface. The clay itself is referred to the Chillesford Beds, which are generally considered to be older than the Forest Bed group of Norfolk. But in many places a mass of sandy gravel is intercalated between these Chillesford Beds and the stony loam. It is generally more pebbly than the Mid-Glacial deposits, and exhibits a more marked alternation of coarser and finer materials.[1] But this gravel, like the Forest Bed group, is generally considered anterior to the Glacial Epoch.

The boulder clays, as already stated, extend to the neighbourhood of London, and good sections are exposed at Totteridge about 300 feet above the sea, and at various localities near Muswell Hill, Finchley, and Hendon.[2] In places they are underlain by gravels, which probably correspond with the Mid-Glacial series mentioned above, and occasionally include thin seams of clayey material. They vary in colour from bluish-grey to reddish, and contain, as usual, fragments of chalk and flint (the former commonly more or less rounded, and often striated), of red chalk,[3] of various Jurassic rocks (and fossils

[1] The Westleton Beds of Professor Prestwich and many authors.

[2] It has been found in these places down to about 175 feet above the sea. Dr. H. Hicks, *Quart. Jour. Geol. Soc.*, xlvii. (1891), p. 575.

[3] This interesting rock first crops out in Hunstanton Cliff in Norfolk, and ends at Speeton Cliff, south of Filey in Yorkshire.

from the same), of grits (some probably from the Carboniferous system), of granite, basalt, and other far-travelled rocks, together with septaria from the London Clay and quartz pebbles. The margin of this boulder clay, which appears to form, speaking in general terms, one deposit, retreats northwards in going west from this its southern limit,[1] and ceases in various parts of Bucks, Oxfordshire, Warwickshire, and Worcestershire; though gravels with fragments of similar rocks extend for a considerable distance to the south, and some of these may be of the same age. The finer materials of the boulder clay appear sometimes to be derived from Tertiary or Secondary clays in the neighbourhood, but commonly correspond more closely with argillaceous strata which outcrop at some distance to the north. The same statement generally holds in regard to the pebbles and fragments. The chalk, the flint, the various Jurassic, the Carboniferous, and other Palæozoic materials, and the numerous crystalline rocks, indicate a derivation from northern and sometimes far distant regions. For instance, the chalk in the drifts of Cheshire resembles that of Antrim; the chalk (and the flint) in East Anglia are more often like that of Yorkshire than that of the region south

[1] It stops short at the northern edge of the Thames Valley. No boulder clay has been found down the slope of the valley, nor in the bottom, nor on the southern side. Whitaker, "Geology of London," i. p. 322 (Mem. Geol. Survey). Perhaps the recent discovery of a boulder clay at Upminster in Essex may require this statement to be slightly modified.

of the Wash.[1] Similar chalk and flints are present (with red chalk) in the boulder clays of Middlesex, in which also Jurassic fossils are not rare,[2] and large fragments of shale from the Kimmeridge Clay occur in the centre of Essex. In the boulder clay of that county specimens of rock from the Cheviot Hills have been found. The general character of the fragments in the Yorkshire drifts has been already mentioned, and it would be easy to multiply instances which show that the rule of a northern origin, and sometimes a distant one, holds generally good.

We must now refer more particularly to the distribution of the great streams of boulders which are known to originate at certain centres of dispersion. These boulders vary in size from a few cubic feet to several cubic yards, being sometimes fairly rounded, but more often subangular or quite uneven. They occur both in the boulder clays and in the intermediate gravels, but more often they are scattered singly over the surface, seeming to play the part in the lowlands of perched blocks in the highlands. The main streams radiate from the following centres:—(1.) Kirkcudbrightshire; (2.) the English Lake District; (3.) Wasdale Crag; (4.) the Arenig region of North Wales. There are, in addition, some minor centres of dispersion, of which a brief notice will be given in conclusion.

[1] The great erratics, however, of Norfolk are certainly of local origin.

[2] *E.g.*, *Ostrea dilatata* (Oxford Clay) and *Gryphæa incurva* (Lias).

(1.) Kirkcudbrightshire.

The granite of this region can be identified with comparative ease. Doubtless it is associated with greenstones, felstones, and sedimentary rocks of the Palæozoic series, which are derived from the same quarter, but of the starting-point of these it is less easy to be certain. Boulders from Criffel and its neighbourhood are strewn on the Cumberland plain, and over a fringe of the western coast nearly as far as the estuary of the Duddon. They reappear in the neighbourhood of Blackpool, and are scattered over Lancashire, though they become very rare to the east of Manchester. From this city the eastern boundary of the dispersion "crosses the western slopes of the Pennine Hills to the interior of the very hilly and almost treeless region called Macclesfield Forest."[1] Here the boulders occur up to a height probably of 1400 feet above the sea, not far from, and about a couple of hundred feet above, the well-known locality near the Setter Dog, at which, as already mentioned, marine shells have been found. From this point the boundary line of the dispersion runs roughly southward by Stoke-on-Trent, Stafford, and down the valley of the Trent to beyond Rugeley.[2] The southern margin extends to Bushbury Hill, and by the neighbourhood

[1] D. Mackintosh, *Quart. Jour. Geol. Soc.*, xxxv. (1879), p. 425.

[2] Mr. Mackintosh (*loc. cit.*) states that he could not find any traces of this dispersion at Lichfield, about seven miles from Rugeley, and a short distance away from the actual valley.

of Wolverhampton to Bridgenorth, whence it curves back by Buxton in Shropshire towards Church Stretton. In parts of this southern zone the erratics are very abundant, and the majority of these lie between 300 and 600 feet above the sea, though occasionally they attain a slightly greater elevation. Of these Mr. Mackintosh says: "The great Criffel concentration is somewhat crescent-shaped, the convex side being the S.S.E., or the side farthest from the source of the dispersion. In this respect it bears some resemblance to a terrestrial glacial moraine. Its length, from the neighbourhood of Bridgenorth to the neighbourhood of Bushbury, may be roughly estimated at about fifteen miles, and its breadth about four miles." The largest boulders seen by him in this district measured $5 \times 3\frac{1}{2} \times 3$ feet, and $4\frac{1}{2} \times 4 \times 3$ feet, and there must be, as he thinks, many thousands more than $3 \times 2 \times 2$ feet. In form they are rough, being subangular, and often angular; indubitable glacial striation is extremely rare. From Shropshire the margin of the dispersion, so far as it can be traced, runs northward into Cheshire,[1] where these boulders are scattered over the plain, and are abundant on the Wirral peninsula. They are also found on the Delamere and Peckforton Hills up to about 650 feet above the sea, being sometimes as much as a couple of cubic yards

[1] The line runs roughly from near Chester (the boulders are not common to the south of that city) by Mold, passing east of Oswestry to Cardington near Church Stretton.

in volume. Boulders, generally small, occur in North Wales near the coast as far west as Moel Tryfaen, and even have travelled inland to the neighbourhood of Denbigh, though this is an exceptional case.

(2.) The English Lake District.

These boulders consist of various felstones, for the most part compact and greenish in colour, of volcanic breccias, ashy slates, and compact argillites, which have a similar composition, and, in the last-named case, are not always readily distinguishable from true igneous rocks, and of reddish granites. These last occur about Buttermere and in the Eskdale district. Their outcrops, as a rule, lie below the 800-foot contour line, but they rise in the latter as high as 1049 feet (near Devoke Water), and 1286 feet (south of the south-west end of the Westwater Screes escarpment). The various erratics belonging to this group are scattered over an area which agrees in the main with that already described, but in Shropshire they extend slightly to the west of its limit; they become much less numerous in the neighbourhood of its southern fringe,[1] and they extend, as might be

[1] They are, however, unusually numerous, and sometimes of large size, in the neighbourhood of Burton in Shropshire, up to nearly 800 feet above sea-level. Here the sudden ending of the boulder stream "differs from the great Criffel terminal concentration in its terminating suddenly on its up-stream as well as lee-side." The area covered by large boulders is about one mile and a half in length, and one mile in breadth.

expected, distinctly farther towards the north-east in Lancashire. They are abundant in the neighbourhood of Manchester; they have been found up the Ribble valley as far as a line joining Longridge with Rochdale, and over the western spurs of the Pennine Hills, where they reach an elevation of above 1100 feet. They attain heights above the sea equal to that of the Kirkcudbrightshire dispersion, pebbles of Eskdale granite having been found on Moel Tryfaen, and boulders near the Setter Dog in the Macclesfield district. In North Wales they are generally restricted to the slopes of the hills overlooking the coast, and appear not to have made their way, in any case, more than a few miles inland.

(3.) Wasdale Crag.

Wasdale Crag, a mass of granite, rises between the tributaries of the Eden and the Lune to a height of about 1600 feet above the sea, the lowest boundary of the outcrop of this rock coming down to about half that elevation. In outline this mass is rather irregular, the greatest length being about two miles, and breadth nearly a mile and a half. Shap granite, as it is commonly called, is easily recognised, large crystals of reddish felspar being conspicuous in a fairly coarse matrix, of which there are lighter and darker varieties. These erratics have travelled down the valley of the Leith, and over Crosby Ravensworth Fell to that

of the Eden, which they descend to within some four miles north-east of Penrith. Towards the south they have been tracked by Tebay on the Lune and by Kendal, to the north of Carnforth, near Morecambe Bay, and even as far as Hest Bank, north of Lancaster. But the most important dispersion is towards the east. Boulders of Shap granite occur on Stainmoor Gap on the Pennines at a height of about 1400 feet above sea-level, the watershed itself rising in places up to 2000 feet; and beyond this range they are scattered over eastern Yorkshire as far as the sea, being found along the coast from Redcar to the district of Holderness,[1] embedded not unfrequently in the masses of boulder clay which have been already mentioned in these pages.

(4.) The Arenig Region.

The most characteristic rock in this dispersion is a greyish to greenish-grey felstone, generally rather pale in colour, usually compact, and sometimes streaky in structure. This can be traced up to, and is identical with, masses of ancient lava which occur in the Arenig and other neighbouring mountains in Wales. These erratics[2] have been traced in a north-

[1] According to Mr. Mackintosh (*Geol. Mag.*, 1871, p. 3'2), they range inland as far north as the neighbourhood of Durham, and as far south as Royston (rather south of the line of the Humber).

[2] According to Mr. Mackintosh, they are generally very much larger and very much less rounded than those derived from the Lake District. The greatest height at which he has found these

easterly direction to slightly beyond Denbigh. "Terminal concentrations (so far as Wales is concerned) are numerous in the neighbourhood of Llangollen; and there is a remarkable one around Eryrys, near Llanarmon." According to Mr. Mackintosh, the boundary-line runs from Denbigh eastwards to near the estuary of the Dee; then southwards by Chirk, Gobowen, Whittington, and Welsh Frankton (near Ellesmere), from which neighbourhood the main stream advances towards Staffordshire. Broadening out in the shape of a fan, it extends in an E.S.E. direction as far as the valley of the Trent beyond Rugeley, whence its margin runs very roughly southwards to near Birmingham, and thence south-west to beyond Bromsgrove in the Severn Valley. Its western limit runs through Shropshire to the neighbourhood of Church Stretton.

These erratics are scattered over both high and low ground. In the valley of the Severn, for instance, boulders four or five feet in length may be seen not unfrequently lying by the roadsides in the neighbourhood of Bromsgrove, and they also occur on Frankley Hill, a prolongation of the Clent range, a few miles farther to the north and on the eastern side of the river. A cutting made in the neighbourhood for a railroad some years ago exposed

is 1900 feet, and the longest one measured 17 feet. They are not unfrequently 10 or 12 cubic yards in volume, and occasionally from this to about 60.

a considerable thickness of stratified sand, sometimes clayey, overlying Permian deposits. Boulders occur in the former, though apparently they are not common. A later excavation opened close to some of the erratics, and almost on the summit of the hill, showed boulder clay. Two of the felstone blocks are of considerable size, the larger measuring $4 \times 4 \times 2$ feet. Besides these Welsh felstones is a greenstone, probably from the same region, and two blocks of basalt, like that of Rowley Regis.[1] The highest part of this hill is about 800 feet above the sea, but three felstone boulders occur on Romsley Hill, in the same neighbourhood, at a height of 897 feet. Here they rest on Permian breccia. Near to the end of the dispersion also the erratics from Wales reach considerable heights above the sea, and, what perhaps may prove to be of greater importance, occur at very different elevations. In the valley of the Trent around Rugeley they are, as already stated, by no means rare. Here the river is about 220 feet above sea-level. From the meadows a little above this elevation they occur up the slopes of the valley, though they are not found on the high moorland forming the northern end of Cannock Chase, a hilly plateau which ranges up to about 770 feet above the sea. Blocks, however, lie on the slopes of the same plateau, above the valley of the Sow

[1] Report of Erratic Blocks Committee, British Association Report, 1879, p. 135.

(a tributary of the Trent coming from the direction of Stafford), and are scattered plentifully at heights of about 500 to 600 feet above the sea on the upland district traversed by the road joining that town with Cannock,[1] viz., on the slopes facing towards the west and overlooking the valley of the Penk,[2] so that they have a vertical range of quite 380 feet. The hill region, on which they are wanting, cannot be more than about four miles across.

It may be convenient, before speaking of the minor areas over which dispersion from some initial mass can be proved, to call attention to certain facts connected with the four preceding cases, which require to be kept in view in forming any hypothesis as to the agency by which the boulders have been transported.

(1.) The areas of distribution, which are apt to be either markedly limited or prolonged in particular directions, are more or less fan-shaped.

(2.) The Scotch and Lake District boulders, over a large part of their areas of distribution, occupy common ground, the erratics being mingled together

[1] One flattish boulder, measuring about $8\frac{1}{2} \times 6\frac{1}{2}$ feet, and rising about two feet above the turf, is as nearly as possible on the 600-feet contour line, near the village of Huntington.

[2] The greatest elevation at which I have found erratics in this district is not less than 700 feet above the sea, and the ground itself seldom overtops this contour line. Between 500 and 600 feet they are fairly common, scattered sporadically, possibly bearing some relation in their distribution to the contour of the ground, and without any indications of boulder clay. Rocks from the Lake District appear to be more common than those from Scotland, and both than those from Wales; but there are, of course, many felstone-like rocks, as to the locality of which one cannot be certain.

on the southern marginal fringe from its extreme east to its extreme west.

(3.) The Arenig boulders are rather limited in their distribution towards the north-east and east, but stream out as from a gateway near Chirk (apparently following the valley of the Dee, which, however, they desert when it turns northwards), and travel diagonally across the stream of the joint Scottish-Cumbrian dispersion, overshooting it by some fifteen or twenty miles in a south-easterly direction, but not reaching quite so far to the west in Shropshire.

(4.) The distribution of boulders from Wasdale Crag is comparatively quickly arrested to the north and the south, no instance (so far as I remember) being recorded of a specimen of Shap granite occurring on the lowlands of the larger part of Lancashire or in Cheshire; in other words, these boulders have not followed the example of the Lake District erratics in ultimately mingling in a common stream with those from Criffel. But in an eastward direction they have made their way across the Pennine range, and have been scattered in great numbers as far as the sea. Thus they have travelled right across the path of the rock fragments in the drift of Eastern England, which, as already stated, have been derived from northern sources.

Whatever hypothesis be advanced to account for the distribution of the erratics, it must be consistent with the facts recapitulated under these four heads.

Some minor centres of dispersion may be noticed in conclusion. The more northern parts of the Pennine Chain have been the source of erratics which are scattered in a general southerly direction about as far as the neighbourhood of Skipton in Yorkshire. The dispersion from the Cheviots, in which, so far as I know, the boulders are generally small, has been already mentioned; and the basalt mass of Rowley Regis has given rise to boulders which have travelled in some cases for distances of between four and five miles,[1] in directions ranging from rather west of south to north-east.[2] But the hills of Charnwood Forest, as might be expected from their rather abrupt rise and bold outlines, have formed a centre from which a considerable number of boulders, sometimes of fair size,[3] have been distributed. Rocky crags and ridges are common on the upper parts of these hills, which rise generally from 700 to 900 feet above the sea; and in the process of quarrying considerable areas are often stripped of boulder clay or of old soil, and afford excellent opportunities of examining the original rock surface. As a rule, it is rough and ridgy; neither *roches*

[1] In the Midlands, boulders occur at various levels plentifully up to over 600 feet, and occasionally higher. Sometimes they have crossed over hills, sometimes followed the lines of valleys. Local erratics are intermixed with those from a distance, and for the former there are distinct centres of dispersion. See Report, Erratic Blocks Committee, British Association Report, 1890, p. 340.

[2] F. W. Martin, *Proc. Birmingham Phil. Soc.*, vii. p. 85. One at Romsley (Clent Hills) is 900 feet above sea-level.

[3] That is, containing from ten to twenty cubic feet, and occasionally more.

moutonnées nor any certain sign of the action of glaciers is to be seen, though occasionally a very few inches of rock appear to have been worn away from the crest of a ridge. Blocks, however, in considerable numbers, undoubtedly have been dispersed from the higher ground; in many cases these have not travelled more than a mile or two, but erratics of Mount Sorrel granite, of the syenite of Groby or Markfield, and of the porphyritic felstones of the northern district, have been traced over an area to the south and the west of the Forest for distances of more than twenty miles.[1]

In the south-west of England, so far as I can ascertain, true boulder clay has not been discovered, though drifts occur which are suggestive of glacial conditions, and erratics are occasionally found, both in Cornwall and Devon, which must have travelled for considerable distances.[2] These indicate, so far as they can be identified, derivation from localities farther to the west. In Pembrokeshire and the adjoining district erratics are often abundant, as may be seen near St. Davids. At present no systematic attempt has been made to trace them up to their sources, but they have probably come from the higher ground inland, that is to say, roughly, from the north-east. Some boulders have been found in Glamorganshire, as near Bridgend, by

[1] Hill and Bonney, *Quart. Jour. Geol. Soc.*, xlvii. (1891), pp. 96, 97. W. J. Harrison, "Geology of Leicestershire," pp. 45–47.

[2] See summary in Woodward's "Geology of England and Wales," pp. 493–496. Clays containing the remains of an Arctic flora overlie the well-known Tertiary deposit at Bovey Tracey.

Mr. F. T. Howard, on the study of which he is now engaged.

The south coast of England, with one notable exception, affords no "positive evidence of glacial action." This is the well-known deposit of boulder clay near Selsea and Pagham Harbour, which has been the subject of several papers, the last[1] by Mr. Clement Reid of the Geological Survey. He states that the Bracklesham Clay (Eocene) is covered by a hard greenish clay, which contains, together with fossils derived from the former, marine mollusca of Pleistocene age, occasional large chalk-flints, and various erratics. This deposit, about two feet in thickness, is covered by a stony clay (with numerous re-deposited erratics) about six inches thick, which passes up into an estuarine mud (with characteristic mollusca), also two feet thick. The whole is covered by a mass of gravels, sands, and loam. The erratics consist of crystalline rocks—granites, greenstones, and felstones—and sedimentaries representing the Upper Greensand and Tertiary formations. Of the locality from which the first have been derived it is difficult to be certain. Some of the granites present a general resemblance to those of Brittany, though one specimen is more like that of Cornwall. The crystalline rocks, however, are much out-numbered by the sedimentaries, and the character of these, besides the not infrequent presence of indisputable specimens of Bognor Rock

[1] *Quart. Jour. Geol. Soc.*, xlviii. (1892), p. 344.

(Eocene) and of Bembridge Limestone (Oligocene), makes it certain that most of the erratics came from the west or south.[1] As to the means of transport, floating shore-ice finds most favour with geologists.

There is general agreement as to the majority of the facts mentioned in the preceding pages, but the greatest discord exists as to their interpretation. In regard to this, geologists, broadly speaking, may be divided into two schools: of which the one attributes most of these deposits to the action of land-ice, supposing certain well-stratified beds to have been formed in extra-morainic lakes. It maintains that the land as a whole stood during the Glacial Epoch at a somewhat higher level than at present, though it admits the possibility of slight local submergence in the neighbourhood of the present coasts. The other school believes in much greater changes of level, in consequence of which the land at first was rather higher than it is at the present time; then it slowly sank until the submergence on the western side of England amounted to not less than 1400 feet, but on the eastern it probably was not more than half as much. By this school, the boulder clays in the main, and the Mid-Glacial sands and gravels, are supposed to have been deposited under water, being diverse in date and composite in origin. In some cases, as in the mountain regions generally, and in the more

[1] Many of these probably have not travelled more than about twenty miles. Mr. Reid figures a striated fragment.

immediate neighbourhood of these, the clays may be true "tills," the leavings of great glaciers (possibly sometimes confluent as ice-sheets), similar to those which are found in the Swiss lowland; in other cases, they consist of materials extruded under water from beneath the ice, and drifted away by bergs and by currents; while at greater distances from the mountains, and over most of the lowland of England, they are chiefly due to the action of shore-ice,[1] which at the breaking up of the winter drifted away, and, as it melted, either dropped its burden on the submerged land surface, or left it on the projecting shoals and islands. Thus the stratified sands and gravels in some cases may be contemporaneous with boulder clay, though formed at a greater distance from the source of supply; in others, may be due to the sorting out of materials from somewhat older deposits; while in those where they occur at the higher levels, or are most widely and regularly outspread, they may be indicative of an amelioration of temperature and a marked recession of the glaciers.

The views of the former school—the advocates of a great extension of land-ice—are represented by the following summary. Glaciers radiated from Scotland, Ireland, the Lake District, Wales, and the northern part of the Pennines (see Map facing page 120). The ice-streams from Galloway, Cumbria, and Ireland

[1] As described by Captain Feilden in the account of the Arctic region of America, p. 53.

became confluent, forming the Irish Sea glacier (as it was termed by the late Professor Carvill Lewis), which took a southward course. It met and fairly conquered the Welsh glacier, sweeping over Anglesea, and even annexing the northern fringe of the coast of Wales.[1] It climbed Moel Tryfaen, where the gravels and sands, like those of some other places, are composed of the coarser washings of its bottom moraine, and contain shells which were scooped up by the ice as it travelled over the bed of the Irish Sea. Wales, however, appears not to have yielded without a struggle; the pressure of its home-made ice, or the resistance of its mountains, forced the northern mass to bifurcate, one arm invading the English Midlands, while the other travelled more smoothly, in obedience to the law of gravitation, down the bed of the Irish Sea, and perhaps ultimately overflowed St. David's Head. The ice from the Cumbrian Hills, though permitted to join the invading host, was apparently made to feel its inferiority, and was "shouldered in upon the mainland;" indeed, the Irish Sea glacier (*i.e.*, the ice from Scotland) seems to have actually trespassed up the valley of the Ribble, and to have deposited its erratics in the neighbourhood of Burnley.

The northern ice appears to have swept down upon

[1] The line of confluence between the two sheets of ice is placed generally about half a mile from the shore, but up the broad valley of the Clwyd the invader advanced as far inland as Denbigh.

Wales as irresistibly as the northern nations upon Rome. This is proved by the evidence of the glacial deposits on the north coast of the Principality. They exhibit (in ascending order) the following sequence:—(1.) Boulder clay with Welsh erratics and no shells; (2.) boulder clay with northern erratics and shells; (3.) sands and gravels with northern erratics and shells; (4.) boulder clay with northern erratics and shells. "The interpretation is clear:[1] in the early stages of glaciation the Welsh ice spread without hindrance to, and laid down, bed No. 1; then the northern ice came down, bringing its typical erratics and the scourings of the sea-bottom, and laid down the variable series of clays, sands, and gravels which constitute Nos. 2, 3, and 4 of the section." The great Irish Sea glacier ran along the range of hills parallel to the estuary of the Dee at an altitude of about 900 feet above sea-level. Traced to the south-east, its surface is proved to have risen, till, at Frondeg, north of the embouchure of the Vale of Llangollen, it reaches a height of 1450 feet. Thence it falls to 1150 feet at Gloppa, after which its exact limit cannot be traced on the Welsh border, but its boundary—we might almost say its terminal moraine—may be followed from Shrewsbury *via* Burton, Bridgenorth, and Enville.

The Irish Sea ice, when pressed against the Cumbrian coast-line, was forced to split in the neighbour-

[1] P. F. Kendall, in Dr. Wright's "Man and the Glacial Period" (Internat. Sci. Ser.), p. 148.

hood of Ravenglass, and the eastern offshoot proceeded "up the Solway Firth, its right flank spreading over the low plain of Northern Cumberland, which it strewed with boulders of the well-known syenite (granophyre) of Buttermere. When this ice reached the foot of the Cross Fell escarpment, it suffered a second bifurcation, one branch pushing to the eastward up the valley of the Irthing and over into Tyneside, and the other turning nearly due southward and forcing its way up the broad vale of the Eden. Under the pressure of an enormous head of ice, this stream rose from sea-level, turned back or incorporated the native Cumbrian glacier which stood in its path, and, having arrived almost at the watershed between the northern and the southern drainage, it swept round to the eastward and crossed over the Pennine watershed; not, however, by the lowest pass, which is only some 1400 feet above sea-level, but by the higher pass of Stainmoor, at altitudes ranging from 1800 to 2000 feet. . . . This Stainmoor glacier passed directly over the Pennine chain, past the mouths of several valleys, and into Teesdale, which it descended, and spread out on the low grounds beyond. Pursuing its easterly course, it abutted upon the lofty Cleveland Hills, and separated into two streams, one of which went straight out to sea at Hartlepool, while the other turned to the southward and flowed down the Vale of York, being augmented on its way by tributary glaciers coming down Wensleydale. The

final melting seems to have taken place somewhere a little to the southward of York; but boulders of Shap granite, by which its extension is characterised, have been found as far to the southward as Royston, near Barnsley. The other branch of the Solway glacier—that which travelled due eastward—passed up the valley of the Irthing, and over into that of the Tyne, and out to sea at Tynemouth. It carried the Scotch granites with it, and tributary masses joined on either hand, bringing characteristic boulders with them. The fate of those elements of the Solway Firth glacier which reached the sea is not left entirely to conjecture. The striated surfaces near the coast of Northumberland indicate a coastwise flow of ice from the northward—probably from the Firth of Forth—and the glaciers coming out from the Tyne and Tees were deflected to the southward. There is conclusive evidence that the ice rasped the cliffs of the Yorkshire coast, and pressed up into some of the valleys. When it passed the mouth of the Tees near Whitby (? Redcar) it must have had a height of at least 800 feet; but farther down the coast it diminished in thickness. It nowhere extended inland more than a mile or two, and for the most part kept strictly to the coast-line."[1]

The opponents of this hypothesis affirm that it attributes to ice physical properties—a plasticity, almost a fluidity—which it does not now possess,

[1] Condensed or quoted from Mr. P. F. Kendall's statement in the volume cited above.

so far as can be ascertained, even in Arctic or Antarctic regions. In these the great masses appear to move, like the smaller masses in the Alps, in obedience to the law of gravitation, to bifurcate but rarely, except this term be applied to the radiation of glaciers from a central reservoir of ice, which descend, each in a gradually deepening valley, to the lowland: any crossing or overstepping of streams, any "ponding back" of one glacier by another, except as a very limited and local phenomenon, being quite unknown. By this school of geologists some of the graver difficulties which arise from referring these glacial deposits of Britain—both boulder clays and gravels—to the direct action of an ice-sheet are thus summarised:—

(1.) The hypothesis fails to explain the occurrence of marine shells in such localities as Moel Tryfaen, Gloppa, &c. Assuming for a moment that a glacier or ice-sheet could pick up and transport shell-bearing sand and gravel from an exposed sea-bed, the organisms would be speedily crushed to fragments if the material was incoherent; and if it were frozen, even then its strength would not be much greater than that of ice. Hence, whether the stuff were pushed in front of the advancing sheet as a terminal moraine, or beneath it, like boulders in a ground-moraine, or were incorporated in the lower part of the ice (as boulders sometimes travel), the frozen blocks would be so broken, crushed, or sheared, that

the shells could hardly escape destruction, and all signs of stratification which the material originally possessed would be obliterated. If, in order to escape this difficulty, the débris is supposed to have been rearranged by the waters of a glacier lake, this must have been a very large one.[1] The existence of such a sheet of water not only is unproved, but also, in view of the physical structure of the country, is a most improbable hypothesis.

(2.) It is difficult to understand how such considerable masses of sand and gravel could have been transported from the sea-bed, unless we attribute great scooping powers to the glacier; but of any such action on loose material we have little evidence, and it must be very exceptional. Dr. Wallace, it must be remembered, though a firm believer both in the extent and in the erosive action of land-ice, admits that the latter fails when the underlying rocks are incoherent.[2]

(3.) The hypothesis of an ice-sheet makes the distribution of the larger erratics and of the smaller boulders in the glacial deposits inexplicable. In regard to this point, three instances may suffice for many.

(*a.*) The erratics of Galloway and of the Lake District are mingled together on the Welsh border

[1] In a small lake there would be neither waves nor currents adequate to produce false-bedding.

[2] Little would be gained by assuming the gravel to be frozen *in situ*, and if the English gravels were frozen, why not the Swiss?

eastwards from the neighbourhood of Snowdon, and beyond it even to the valley of the Trent.

(*b.*) The joint path of these erratics is crossed at its more southern end by those from the Arenigs.

(*c.*) The boulders from Shap Fell stream eastwards from the gap in the Pennines to the Yorkshire coast across the path of the drift from the north, and any deflection which they may undergo towards the south is extremely slight.

In fact, the mingling and crossing of these erratics is without a precedent in existing glaciers, and can only be explained by attributing to the ice of a past epoch physical properties differing, not in degree, but in kind, from those which it still possesses; properties also, the existence of which rests on the necessities of a hypothesis rather than on any direct evidence. If the ice of the Glacial Epoch were like the ice of the present day, the boulders from Galloway would be on the western side of the mass, those from the Lake District on the eastern, and they would be mingled towards its centre. The Arenig boulders would be mostly shoved off in the direction of the Severn valley, and would be unknown in the Trent valley; and those from Shap would have failed to reach the Tees, or would have been shouldered off from the Yorkshire coast.

These difficulties appear yet greater if an attempt be made to realise the manner in which the ice must have gradually gathered at the on-coming of

the Glacial Epoch. First snow would cap the hills; next glaciers would occupy the higher glens; then they would creep down the valleys, until at last, when all the hills were swathed in snow, they approached the lowlands. North Wales, for instance, would resemble first the district about the Ofenhorn, then such an one as the Oetzthaler Alps; in the one case that above the 7000-feet contour-line, in the other that above the 8000-feet. In the third stage it would be more like the condition of the district about the Theodule Pass in the Pennine Alps. Ultimately it might possibly resemble the north of Greenland, but whether it ever arrived at this stage of development must be demonstrated, not assumed. The ice, however, would move, certainly in the first three conditions and most probably in the fourth also, in obedience to gravitation—that is to say, in the general direction of the valleys. Even if it accumulated to such an enormous extent that the masses in adjoining valleys gradually became confluent by overflowing the intermediate shoulders, still, though sundry irregular movements might be caused on the crest of a "divide," the motion of the mass as a whole must be, from first to last, in the direction of the valleys.

Again, the difference in elevation and in physical conditions between the southern upland of Scotland and the Cumbrian hill-region is not sufficient to give the ice of the one any very marked advantage over

that in the other, while the two combined would gain but little on the ice-streams from the Welsh mountains in their race for the occupation of the lowlands, and an invasion of the Cambrian frontier by the ice of Cumbria and Caledonia would thus become impossible.[1] But the boulders, which were scattered over the surface of the land when the fall of temperature began, must move in the same direction as the ice itself. Those on the summit of the higher plateaux very probably would not be materially disturbed, but those on the more shelving ground would "drift slowly with the current," whether they were embedded in the ice or pushed along beneath it, or even shoved in advance of it.

The ice is often assumed to have been thrust up opposing slopes by the pressure from behind. For instance, the mass which crossed the Wash must have risen 300 feet above it on the plateau of Suffolk; that which had flowed over the bed of the Irish Sea must have welled up to from eleven to fourteen hundred feet above it at Gloppa, the "Setter Dog," and Moel Tryfaen; even the last traces of the ice-sheet at the northern margin of the Thames

[1] Snowdon and the head of the Solway Firth differ in latitude by about two degrees. This, in accordance with the usual formula (temperature of place in latitude $a = 41.8 + 39.7 \cos 2a$), gives a normal difference of temperature 2.7 F. (viz. 30.9 − 28.2 F.). This would be equivalent to an addition of about 800 feet to the northern mountains; those of Southern Scotland would then be about equal to those of Wales as ice-accumulators, but would possess a slight advantage so far as their configuration went.

valley are found from two to three hundred feet at least above Ordnance datum. For such an upthrusting to have occurred, the "head" of ice must have been enormous; and of this, as will be seen, there is no evidence.[1] The case of the welling up of the Alpine ice on the flanks of the Jura is no real parallel, because there the erratics were transported on the surface of the ice, while in Britain they must have travelled beneath it.[2] There is, however, some evidence actually unfavourable. The volume of the ice which radiated from the Scotch highlands in a westerly direction cannot have been less than that which descended southwards from Galloway and the glens draining to the Firth of Clyde. But the peaks of the Cuchullin Hills in Skye, so far from being overwhelmed, were evidently independent centres of dispersion.

The ice-sheet, also, which flowed outwards from the mountains of Northern Scandinavia must have been on a still grander scale. On the west coast, crossed by the 68th and 69th parallels of latitude, the rocky chain of the Lofoten Islands trends gradually outwards from the mainland to shelter the waters of the Vest Fjord. The central islands are bold rocky

[1] It is admitted (see p. 168) to have been not much more than 800 feet thick at Whitby, viz., over 200 miles away in a straight line.

[2] Or, at any rate, embedded in the lower part. There is no reason to suppose that the higher aiguilles in the Alps were ever concealed, but if an ice-sheet had existed in the British hill-regions, little or nothing in the way of rock could have remained above it.

peaks, rising, at present, to a height of some 3000 feet above the sea. These were never enveloped in the inland ice. The scenery of the boldest part, from south of Svolvaer to well north of the Raft Sund, though on a slightly smaller scale, might be compared with that of the western aiguilles of the Mont Blanc range if the sea were to wash the contour-line of 10,000 feet, and the ice were almost wholly melted away. As these aiguilles now rise amid the snow-fields, so did the peaks of the Lofotens in the Glacial Epoch. The valleys between them were filled with névé, but only to a very moderate depth; their ice-streams became confluent, so that the marginal hills and the rocky islets—anything towards the exterior of the districts which does not rise at the present time more than a very few hundred feet above the sea —are one mass of *roches moutonnées*. The Alps also afford evidence, by no means unimportant, as to the thickness of an ancient ice-sheet. In some parts, where the heads of the valleys are often about 8000 feet above the sea-level, and the ridges rise from 1500 to 2000 feet higher, the traces of vanished glaciers and snowfields are abundant. But over such a region the ice has not been piled up to an almost indefinite thickness. The névé in the basins among the craggy ridges may have accumulated to a depth of some five or six hundred feet, and from this the ice is seen to have slowly become thicker as it proceeded on its path towards the main valleys. The descent into

these, say for one to two thousand feet below the 7000-feet contour-line, is generally rather rapid, and the trough thus formed has been filled more than brim high with the accumulated ice. In these valleys, no doubt, it attained to a great thickness, for they are the main drains of the mountain region, and water must pass away more slowly in a solid form than in a liquid one; but even here it may be doubted whether the thickness of the ice ever exceeded 3000 feet, and in numerous cases it was considerably less.[1]

The generally rounded contours both of the Scotch Highlands and of the Scandinavian mountains would be more favourable than those of the Alps to the accumulation of a great central field of névé (as in Greenland), but the comparatively restricted area of each, and especially of the former, must not be forgotten in any reference to that Arctic country. The difference of temperature also between Switzerland and the more northern regions of Europe would probably be greater in Glacial times than it is now; still this is unlikely to have been more than between two places ten degrees apart in Greenland. Moreover, in considering the possibility of the advance of ice from Scotland towards England and Wales, we must remember that as soon as the bed of the Irish Sea, and that near the coast of Scotland, became dry land, the

[1] This fact is in favour of the assumption that when the Alpine ice extended to the Jura, the temperature in the Swiss lowlands cannot have been higher than about 32° F., for if it had been, the supply of ice would not have sufficed to carry the glaciers so far.

bulk of the Highland ice would move westward, with a slight northward trend, and only that from the basin of the Clyde and from the uplands to the south of it would descend towards England and Wales. This would be a consequence of the configuration of the sea-bed, assuming, of course, that the ice moved in accordance with the law of gravitation.[1]

There is a similar difficulty in understanding how Scandinavian land-ice ever can have extended to the eastern margin of England. From the end of the Skager Rack a channel about 400 fathoms deep skirts the coast of Norway to between the 62nd and 63rd parallel of latitude, when it gradually opens out into the deeper water farther north. If the land were raised 600 feet, a great fjord, wide as the Straits of Dover, and still about 300 fathoms deep, would separate Scandinavia from the low plains which had replaced the North Sea; and this fjord, so far as one can judge from Greenland, would be an impassable barrier to the advance of the ice. If, however, an elevation of nearly 2500 feet be assumed, then the fjord would be converted into a broad valley. But the Scandinavian ice, in obedience to the law of gravitation, would first enter and then descend this valley until it reached the Northern Atlantic.

Two hypotheses are devised to escape this diffi-

[1] Because the submarine plateau connecting Scotland by way of Jura and Islay with Ireland would form a "divide," which from the first would part the ice-streams, and divert them in opposite directions.

culty. One assumes the bed of the valley to have been so flat that the ice was practically independent of gravitation, and thus was forced up the opposite slopes by the pressure from behind, after which it made its way across the plateau to Britain. This hypothesis, however, postulates a rigidity in ice which would lead to very great difficulties; for unless this be assumed, the huge glacier, instead of crossing the valley, would descend it, that being, at any rate, the direction of least resistance.[1] But, in addition to this, an elevation of 2500 feet, at that period of the earth's history, ought to have converted all England into a gathering ground of snow and ice, so that the passage of the invader, when it had crossed the frontier ditch, would have been barred by the hosts which were already encamped upon the plains.

The other hypothesis assumes that the above-named channel had no existence at the time when the Scandinavian ice-sheet advanced over the bed of the North Sea; namely, that its erosion did not begin till late in Glacial times. But before this suggestion can be accepted, we require valid evidence from other quarters in favour of a physical feature of such magnitude —one far more gigantic than the gorge of Niagara—

[1] The distribution of erratics by varying currents in an ice-sheet would thus become inexplicable. It might also be asked why the ice-streams from the Tweed, the Firth of Forth, and other northern valleys, should turn southward? As the water must have flowed northward, a slope gently descending should have proved a more attractive course than one gently ascending in the opposite direction.

having been produced in a time comparatively short. The dimensions already mentioned, especially when account is taken of the probable character of the rocks in which this valley is excavated, seem a very grave obstacle to this way of escaping the difficulty.

But it must not be supposed that the advocates of land-ice have no objections to advance against the submergence hypothesis. The more serious of these may be summarised as follows:—

(1.) The absence of any certain proofs of marine action, such as well-marked beaches, cliffs, and sea-caves, except at low levels and near existing coasts.

(2.) The absence or extreme rarity of stones or rock surfaces encrusted by such organisms as serpulæ or barnacles, or bored by lithodomi, or of shell-beds representing the actual home of the molluscs, or of the joined valves of lamellibranchs, together with the frequently fragmental and scratched condition of the shells.

(3.) The absence among the molluscs discovered of any indication of a zonal arrangement, or of any forms which are significant of deep water; though such deposits ought to occur on the lower ground, since a submergence of over 200 fathoms is asserted. It is also pointed out that the shell-beds contain molluscs which have different habits of life, and that their fauna, though generally boreal, includes some species which have a more southern aspect.

(4.) That the shells are associated with transmarine boulders, and do not occur within any of the great centres of glaciation, except it be on the lee sides of them.

All these objections are such as cannot be lightly put aside, and require an answer. That which is generally returned to the more serious of them may be stated in outline as follows:—

The mixture of species of different habitats in shell-bearing sands or gravels, such as those of Moel Tryfaen or Gloppa, is undoubtedly a difficulty in the submergence hypothesis, though perhaps not quite so great as is sometimes asserted. The molluscs of Moel Tryfaen, according to the late Dr. Gwyn Jeffreys,[1] consist of fifty-five species and three varieties. Of these, the majority are littoral, only a few usually inhabiting depths ranging from 10 to 20 fathoms. But at the present day molluscs from moderate depths are not uncommonly washed up on shores and beaches in neighbourhoods where the sea can run high. This also may explain the mingling of dwellers on muddy, sandy, and rocky bottoms, a difficulty mentioned by the late Professor E. Forbes. Similar anomalies are presented by the shell-beds at Uddevalla,[2] but these must have been beneath the

[1] *Quart. Jour. Geol. Soc.*, xxxvi. (1880), p. 351.

[2] This subject is discussed by Sir H. Howorth, "The Glacial Nightmare," chap. xvi. pp. 714–729, xvii. pp. 828–835. The solution, however, which he favours would not commend itself to geologists of either school.

water, for barnacles and polyzoans have been found attached to the underlying rocks.[1]

Opponents of the submergence hypothesis have also urged that, if it were true, the shells, instead of being found only in exceptional localities, should be comparatively common. This objection, however. would equally apply to the raised beaches on the western coast of Norway, which are usually admitted to have been formed during a submergence, for in them also shells occur but rarely and locally.[2] The objection has been extended, and it has been asserted that if these sands and gravels had been formed by the sea, they ought to be much more common than they are, and that cliffs, wave-worn caves, and rocks pierced by lithodomi should be not unfrequent. The opponents of the land-ice hypothesis reply by demurring to the first assertion—the infrequency of sands and gravels—and by again pointing to the coast of Norway, calling attention to the fact that even here beach deposits are not very common, and the waves only make their marks on the more exposed parts; for among the islands and in the fjords the ice-worn rock may be often seen sloping down beneath the water, and lithodomi, if ever found, are extremely rare.[3]

[1] Sir C. Lyell, "Principles of Geology," chap. xxxi.

[2] So far as my experience goes, this is generally true of raised beach deposits.

[3] Probably most of the Welsh rocks would be too hard to be pierced by these creatures.

One other difficulty which is generally advanced by opponents of the submergence hypothesis may be mentioned here, for, in my judgment, it in reality confronts both the parties, namely, the frequent occurrence of erratics at levels higher than that of the parent rock. Advocates of the land-ice, non-submergence hypothesis believe these to have been pushed uphill by the mass as it advanced; their opponents maintain that in such cases the thrust due to the weight of the upper or more central part of the ice-sheet must have been very great, and that no evidence can be produced to show that in such a region as Britain this pressure would often be sufficient to become a motive force of any real importance. The erratics, as a rule, must have travelled either between the ice and the underlying rock or embedded in the lower part of the former, for in cases where they have come from a merely highland region, and the accumulation of ice was great, they cannot have started by any possibility on the surface of the latter. For instance, in the well-known case of the boulders of Shap granite, the summit of Wasdale Crag, whence they have come, is only 1656 feet above the sea-level, yet erratics from it have passed "over the limestone ridge of Orton (1000 feet), across the Vale of Eden, over the limestone ridge of Stainmoor (1400 feet at the pass, over 2000 in other places), down the Vale of York, over the Oolitic ridge (300 to 1485 feet), and over the Chalk hills (500 to 800 feet) to

Flamborough Head."[1] Obviously, the ice must have been piled very deep over the Lake District in order to produce a thrust sufficient to carry the outer portion of the sheet up to and over even the lowest part of the Chalk wolds (500 feet), which is more than eighty miles away in a straight line. This, however, is not the only difficulty. Such a panoply of ice would not be assumed in a single night, or even in a few years. As the seasons became gradually colder, the mountainous districts of Britain would pass through phases which are represented in such a region as the Alps in ascending from the snow-line. First, "glaciers of the second order" would be formed in corries and the heads of valleys; next, these, as the mountains donned larger capes of snow, would enlarge into ice-streams; then, as the white robes grew more ample, the glaciers would become confluent, till at last they would even overflow the lower ridges which separate valley from valley, and would trespass upon the lowlands as an ice-sheet. It is, therefore, probable that the bulk of the débris, which had accumulated on the surface of the district in pre-Glacial ages, would be transported in the direction of the main lines of drainage, and it would have been almost wholly cleared away from the higher ground before the ice attained to its greatest development. From what source, then, is a new

[1] Woodward, "Geology of England and Wales," p. 487. It does not of course mean that the boulders passed over the highest part of the Oolite and Chalk ridges. They are, however, found on Stainmoor Gap at a height of over 1700 feet.

supply to be obtained? for it has not yet been proved that glaciers are able to tear up blocks from the bed of hard rock over which they pass.

In addition to these difficulties, which may be regarded as samples of those to be found in other cases when they are subjected to close examination, direct experiment, so far as it goes, indicates that substances heavier than ice sink slowly downwards in it; at any rate, they do so when placed on its surface. I have, however, sometimes noticed that an engulfed moraine reappears below the foot of an ice-fall rather sooner than I should have expected. Accordingly, I have consulted my friend, Professor Karl Pearson, who has given special attention to questions of this kind, as to the possibility of the existence of this upward extrusive movement. After remarking that the motion of a solid body in a viscous fluid is a problem extremely difficult, and in a plastic solid practically unmanageable, if it be treated by strictly mathematical methods, he continues: "Taking some very rough approximations, based upon what seem to me the relative height of a boulder and the depth of a glacier, I conclude that, unless the boulder was of *gigantic* proportions, the differential velocity of the strata of the glacier could not have any sensible effect. If boulders are actually ejected, it is much more likely to arise from the lower slow-moving strata becoming upper quick-moving strata, at a lower point of the glacier, owing to the rapid melting of the superficial ice."

But in a paper communicated to the Geological Society while this volume was in the press, Professor Sollas has shown, by experimenting on a model "glacier" formed of "cobbler's wax," that a substance resembling ice is made to pass over a barrier in its path by the pressure of the mass (at a higher level behind), and that during this process a part of a given layer in the moving material is pushed up to a level above that which it formerly occupied. By this movement an erratic embedded in the ice should be raised; but he has not yet shown whether the upward movement would counteract that in a downward direction, on which Professor Pearson lays stress.[1]

Geologists who believe that these erratics generally have been transported by floating ice during a gradual submergence and emergence suppose that the boulders were frozen into shore-ice, were then floated away with it for some distance, and at last were stranded, this process being repeated as the land sank. "Flotsam and jetsam" always has a tendency to be deposited at the highest level reached by tidal waters.[2] Accordingly, the boulders would be lodged higher and higher as the land went down, and they might even continue their travels after the crags from which they began their journey had disappeared under the

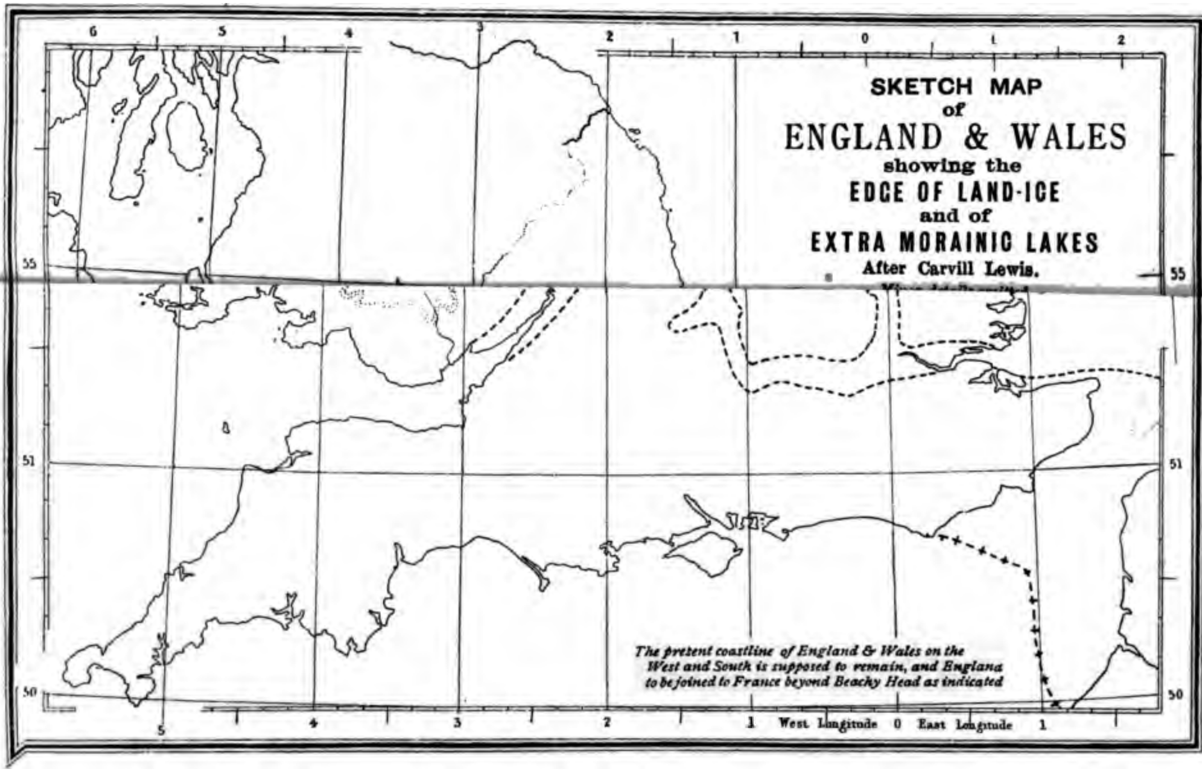
[1] I believe that Professor Sollas is now making farther experiments, in the hope of clearing up this difficulty.

[2] I remember during one unusually severe winter, some years since, seeing the shore of the Humber at low tide quite fringed with great slabs of ice, stranded just below high-water mark.

sea. Such a process is undoubtedly possible; still it must be admitted the large number of boulders which must have been transported in this manner across the Stainmoor barrier constitute a real difficulty. Drifting of ice-rafts, however, would explain the singular mixture of the erratics, as described above, for the direction of the currents would be affected by the extent of the submergence, and would vary to some extent with the season of the year, and floating raft-like masses of ice would be influenced by the winds, which would be still more liable to change. In short, in the present state of our knowledge, a choice has to be made between hypotheses, each of which involves serious difficulties.

An hypothesis advanced some years since by the late Professor Carvill Lewis[1] still remains to be noticed. He believed that, in the time of greatest cold, Scandinavia, Scotland, much of Ireland, Wales, and the higher ground in Northern England were swathed in vast masses of ice, which in most places formed a sheet, but in others local glaciers. The margin of the ice took the following course on the English lowlands (see Map). Starting from the eastern border of Wales, not very far from Welshpool, it crossed the valley of the Severn, and then turning northward near Coalbrookdale, ran in a general N.N.E. direction, modified by the contours

[1] "The Glacial Geology of Great Britain and Ireland," p. 42 *et seq.*


SKETCH MAP
of
ENGLAND & WALES
showing the
EDGE OF LAND-ICE
and of
EXTRA MORAINIC LAKES
After Carvill Lewis.
The present coastline of England & Wales on the
West and South is supposed to remain, and England
to be joined to France beyond Beachy Head as indicated
West Longitude 0 East Longitude
55
51
50

of the country, passing to the west of Stafford near Newcastle-under-Lyme to the east of Macclesfield, whence it ran, bearing now rather to the W. of N., along the slope of the Pennine range. On arriving at the eastern side of this range, if we omit some local irregularities as immaterial in a general description, it took a south-easterly course in the valley of the Nidd, went near York, and then bent round in a great curve to the coast near Whitby. Along this it swept—for the ice now belonged to the great mass which occupied the present bed of the North Sea—trespassing generally upon the land for a few miles, till it crossed the mouth of the Humber, scraped the coast of North Lincolnshire, and finally, near Cleethorpe, turned away in an E.S.E. direction across the sea-bed. By this huge mass of ice the Yorkshire rivers which flow eastward, and those of the Midlands or Eastern counties which take the same or a northerly direction—the rivers, in short, of which the present North Sea is the recipient—were completely blocked, and the accumulated water formed a great lake, the level of which gradually rose until it reached the present 400-feet contour-line, and found an outlet. Beneath this sheet of water, speaking in general terms, the greater part of Yorkshire, Lincolnshire, all Norfolk, Suffolk, Cambridgeshire, and Huntingdonshire were submerged, together with portions of Essex and the Midland countie and considerable tracts in the lower ground

draining to the Severn and the Thames. During a part of the time the land may have subsided below its present level, but at most for not more than 100 feet. Thus Professor Lewis regarded the glacial deposits on the northern side of the above-named boundary as the direct products of land-ice, and those to the south of it as laid down under water, though none the less of "glacial" origin; thus they would be lacustrine as a rule, but in some cases fluviatile, because large streams would issue from the margin of the melting ice-sheet. This hypothesis avoids some serious difficulties, which, as already pointed out, must be encountered if all the boulder clays of England are attributed to the action of land-ice; but it has others to meet which are peculiar to itself. Its opponents maintain that if the glacial beds were laid down on one side of the above line upon land, and on the other under water, they ought to exhibit some fairly well-marked distinctions. Doubtless, as the higher hill regions are approached, deposits can be found which would be universally admitted to be the direct products of an ice-sheet or a large glacier, but it seems impossible to draw any distinctions which have more than a local and merely varietal value between the boulder clays, sands, and gravels of the Yorkshire coast south of Scarborough (which are attributed to land-ice), and those of Norfolk, Suffolk, and Eastern England generally as far south as the valley of the Thames.

Again, while it is admitted that the advance of a great mass of ice in the opposite direction to that of the natural drainage would block the streams and thus form lakes, it is doubtful whether the water could be retained at so great a height as the hypothesis requires. At the present time the way from the principal lake to the south lies completely open through the Straits of Dover. This passage doubtless was then closed, but is there any proof that the land connecting England with France rose to a height at least 400 feet above the present sea-level? Granting, however, the possibility of this (for neither party can bring any direct evidence), the drainage of the Severn and its tributaries must have had a free outlet towards the south-west, for we can hardly venture to assume, and Professor Lewis does not seem to assert, that the northern or western ice-sheet completely blocked the Bristol Channel. Thus all the glacial clays in the valleys of the Severn and its tributary streams, such as the Midland Avon, must have been formed either by rivers or in small local lakes; yet these, in many places, present a singular resemblance to the clays (and the remark might be extended to the associated sands and gravels) of the other region.

A third difficulty was advanced when Professor Lewis gave the first sketch of his hypothesis, namely, that to the south of the supposed moraines of the ancient ice-sheet, boulder clays and erratics, often of

considerable size, occurred at elevations considerably above the contour-line of 400 feet. For instance, the boulder clays overlying shell-bearing sands in the neighbourhood of Wellington (Shropshire), which have been already described, are full 500 feet above sea-level, and the erratics in the Clent district rest on a boulder clay at nearly 800 feet, and occur in one case almost at 900 feet.[1] The first named were admitted by Professor Lewis, when he examined them, to have been deposited in the sea, though he seems afterwards to have gone back from this opinion; the others he considered to be proofs of the existence of an ice-sheet earlier in date and much larger in dimensions than that which he had been tracing in other parts of England.[2] This, however, would have necessitated a complete revision, probably a recasting, of all that he had written about the glacial deposits elsewhere in England; for he had maintained that these deposits belonged to a single age, and that, allowing for minor oscillations, there had been a continuous advance, followed by a continuous retreat, of the ice-sheet. Unfortunately we shall never know how this difficulty would have been overcome, for in the following year he landed in England only to die at Manchester of an attack of typhoid fever, contracted just before leaving America.

Formerly, very many, if not all, the deposits of

[1] See pp. 156, 160.
[2] *Op. cit.*, Introduction, pp. liv.–lxxii.

which we have been speaking—deposits now regarded as in some way or other the results of ice-work—were supposed to be the leavings of great floods; and this hypothesis has been recently resuscitated and advocated by Sir H. Howorth.[1] His book is a perfect mine of information as to the earlier literature on the subject of ice and its work, and contains much acute criticism of the different views which have been advanced by his predecessors; but I have not thought it necessary to discuss directly the "diluvial" hypothesis, which, indeed, seems to find very few supporters among living geologists, because the theoretical arguments advanced by the learned author appear to me inconclusive, and especially to be open to the objection of using for general explanations facts and principles which are only applicable to exceptional cases. Besides this, I have been unable to satisfy myself, after many years' work in the field, during which special attention has been directed to the physical significance of rock structures, that an appeal can be made to floods as agents of destruction and translation, save in particular localities and in very limited areas. In these, no doubt, during the Glacial Epoch, or rather during its incoming and outgoing, floods would be both common and on a considerable scale; but, to my mind, they do not satisfactorily explain either the formation of the glacial drift as

[1] "The Glacial Nightmare and the Flood." 2 vols. 1893. (See more especially chaps. xvii. and xviii.)

a whole, or the distribution of the more important erratics.

A shorter notice may be sufficient for the work of ice in Scotland, because, although much difference of opinion exists as to several matters of detail in this country also, there is a more general accord as to the main question. Geologists agree that at least during a part of the Glacial Epoch the Highlands and Southern Uplands, if not the whole of the Lowlands, were buried beneath ice. How far this extended from the present coast-line is a subject of dispute, as has been already stated, but it is obviously one which pertains rather to the whole of the debatable ground than to Scotland itself. In regard to the latter, the main questions relate to the excavating power of ice, to the evidence of submergence, and to the origin of the tills and boulder clays. Lakes and tarns abound in the Scotch Highlands; submerged basins are detected by the sounding-line in some of its lochs and among the islands which fringe its western coast. These, like similar irregularities on the coast of Norway, are referred by some geologists to the excavating action of the great ice-streams which once radiated from the Highlands, and have been coupled in discussion with the lake-basins of other regions. Upon this vexed question it is needless to enter in detail, and we may content ourselves with referring to the general discussion in the preceding chapter. But we must

endeavour to give a brief summary of the facts chiefly bearing on the other two questions, which, indeed, are rather closely related.[1] These, as might be expected, have received great attention from Scotch geologists.

The proofs of a glaciation, practically universal, are indisputable. The islands in the sea, the rocks on the lower ground, both near the coast and inland, are commonly rounded, smoothed, and scored by ice. The lowlands are often swathed in glacial débris, to a large extent till or boulder clay. The direction of the striations and the trend of the worn surfaces of rock indicate that the ice-sheet extended some distance from the present shore of Scotland, and radiated outwards from its hills, as from a central snowfield. It swept over Caithness in a north-westerly direction, and invaded even the Orkneys and Shetlands;[2] from the Western Highlands it crossed the Minch, and buried the undulating rock surface of the Outer Hebrides. Some geologists, however, consider these islands to have been independent centres of glaciation. Certain it is that the Cuchullin

[1] A mass of facts, very clearly marshalled, will be found in Professor J. Geikie's "Great Ice Age" (the third edition of which appeared late in 1894). A long paper by Sir A. Geikie, in the *Trans. Geol. Soc. Glasgow*, vol. i. part ii. p. 26, though written several years ago, is still a most valuable summary.

[2] This is supposed to be the effect of the union of the Scottish and Scandinavian ice-sheets. That these districts are glaciated is indubitable, but there is some difference of opinion as to the direction of movement and the source of the ice.

Hills show no signs of having been buried beneath an ice-sheet, but produced their own glaciers, like the Lofoten peaks on the coast of Norway, and thus, though they sent their tributaries to swell the masses from the mainland, preserved their local independence. This seems to indicate that the thickness of the mainland ice cannot have been very great. It was, however, according to the author referred to above, sometimes deep enough to pass over hills from five to eight hundred feet in height, and to well up to the level of summits of twice or thrice that elevation. Probably at the same time, *i.e.*, in the earlier part of the Glacial Epoch, the land stood at a greater height above sea-level than it now does. Possibly the coast margin then may have roughly corresponded with the present hundred-fathom line. A number of facts are cited to show that some of the principal rivers of Scotland once occupied channels considerably below the level of the beds over which they are now flowing. The existence of these buried valleys has been proved by borings, and the channels of their ancient tributaries are often cut through and displayed by streams which are still at work. Both are filled up, partly with till or boulder clay, partly with various stratified deposits, and the depth of the principal valleys often indicates that the subsequent elevation cannot have been less than 200 feet, and may very well have been more.[1]

[1] Details are given in "The Great Ice Age," chap. viii.

As to the precise origin of these stratified deposits, it is difficult to be certain. Professor J. Geikie thus sums up the evidence:[1]—"The almost total absence of fossils makes it in many cases difficult to decide whether they are of fresh-water or of marine origin. In some cases, at low levels, it is not unlikely that they are partly one, partly the other. It must be admitted, however, that the absence of organic remains tells more against a marine than a fresh-water origin for the mud, sand, and silt that fill up the buried channels and hollows. . . . The opinion to which I incline is that the aqueous beds now filling up the old hollows and depressions of the land are in large measure of fresh-water origin. But if this be so, it seems certain that they cannot all have been laid down in the old ravines and valleys under conditions like those now obtaining in similar water-courses and depressions. No geologist would admit that the great depths of fine sand, silt, and mud which occupy the buried hollows could possibly have been deposited by such streams as now flow in similar places. In many cases the deep aqueous drifts, as exposed in open section, have quite a lacustrine character."

Marine organisms, however, are found in the glacial clays, or in beds associated with them, up to considerable elevations above sea-level. The upper till often contains fragments of shells, frequently worn or

[1] *Loc. cit.*, p. 118.

striated, and occasionally whole specimens.[1] To some geologists these appear to be proofs that the clay itself was deposited under water; by others they are supposed to have been pushed by the ice-sheet up to and over the land from the sea-bed, where they had lived and died. Beds, however, there are to which the latter explanation hardly seems applicable. At Tangy Glen, near Campbeltown, at a height of 130 feet above sea-level, is a bed of laminated clay intercalated in boulder clay. It contains a few fossil shells, some of them very Arctic in character, together with ostracods.[2] Similar beds occur in Aberdeenshire at heights of from 150 to 200 feet, near Glasgow at various heights to above 60 feet, and in several localities on the estuary of the Clyde and among the neighbouring islands, as, for example, in Bute and Arran. In one case ostracods only, with a few remains of *Elephas primigenius*, *Cervus megaceros*, and *Equus caballus*, were found near Paisley at 106 feet. The memoir just cited describes more than thirty sections in various parts of Scotland, on the east coast as well as on the west, where beds with fossils are either "covered by masses of highly glaciated boulder clay," or "intercalated between masses of boulder clay," or rest upon the boulder clay and exhibit "a very gradual change from old marine to recent estuarine conditions." The

[1] The clay of Caithness, which sometimes reaches a thickness of 100 feet, contains shell fragments from top to bottom.

[2] See Brady, Crosskey, and Robertson, "Monograph on the Post-Tertiary Entomostraca of Scotland." Palæontograph. Soc., vol. xxviii.

fauna in these beds indicates a difference of depth, some of its members being littoral, others deep-sea forms. Species characteristic of either habitat are sometimes found together in the same bed, "evidencing the action of tides and changing currents. They occur sometimes *in situ*, sometimes they are very much broken and fragmentary." Usually these deposits are within a few miles of the present coast, and less than 200 feet above it—indeed, as a rule, not so much as 100 feet. This is true of both coasts; still instances are on record where shells have been found at higher levels, while on the eastern coast, in Aberdeenshire, Banff, Elgin, and Nairn, shelly clays, sand, and gravels have been found up to rather above 500 feet,[1] at Clava (in the valley of the Nairn) at 503 feet, and at Airdrie (Lanark) 526 feet. The Clava section has been recently examined by a committee appointed by the British Association. It was reported to be as follows:—

1. Surface soil and sandy boulder clay .	43 feet.
2. Fine sand	20 „
3. Shelly blue clay, with stones in lower part	16 „
4. Coarse gravel and sand . . .	15 „
5. Brown clay and stones	21½ „

The last deposit (which was not exposed like the others in open section) rested on Old Red Sandstone. The shell-bed (3) appears to continue for a distance of at least 190 yards in a well-nigh horizontal position.

[1] J. Geikie, "The Great Ice Age," p. 139.

"The stones in the overlying boulder clay, and the trend of the glaciation in the neighbourhood, indicate an ice movement from the south-west." The majority of the committee of investigation believed that the molluscs lived and died where their shells are now found —in other words, that they prove a submergence of rather more than 500 feet; but two of its members regarded the Clava deposit as a great erratic which had been pushed or dragged uphill by an ice-sheet from the basin of Loch Ness. On this hypothesis Professor J. Geikie[1] (a member of the committee) thus comments: "Glacier ice has played many strange freaks, but one may be excused for doubting whether it is equal to this remarkable performance. I cannot think it possible that a sheet of clay and sand, measuring 190 yards at least in diameter, could be dragged forward underneath an ice-sheet for a distance of twelve miles from the sea-level up to a height of 500 feet, and yet manage to preserve its horizontality, and to exhibit no trace of deformation or disturbance."

In some districts the lower till rests directly on old or uneven rock surfaces; in others stratified deposits intervene, occasionally containing organic remains, indicative, as a rule, of a fresh-water origin, such as fragments of plants and the bones of terrestrial mammals. The fact that commonly two masses of till or boulder clay can be distinguished, and in

[1] *Loc. cit.*, p. 141.

some cases even three, distinctly separated by stratified muds, silts, and sands, some feet, or even yards, in thickness, indicates that there must have been some climatal variation during the epoch in which they were formed. This is quite irrespective of the question whether these clays containing erratics be directly or indirectly the product of ice, *i.e.*, whether they be the ground-moraines of huge glaciers, or have been deposited beneath the sea. On the climatal question also diversity of opinion exists. Some authors, following Professor James Geikie, regard the more stratified deposits as proofs that a succession of milder seasons occasionally tempered the long age of cold—in other words, of the occurrence of Interglacial Periods; while others consider them to indicate nothing more than oscillations in the volume of the ice, like to, though on a larger scale than, those exhibited by the comparatively small glaciers of the present day. But we must be content with a bare mention of this question, for any adequate discussion would be hardly possible within the limits of this volume.

Glacial deposits are no less abundant in Ireland than in Great Britain, and present very similar difficulties. In all the mountain districts, corries with tarns, moraines, perched blocks, and ice-worn surfaces are frequent, showing that each group, as might be expected, has been the centre of a glacier system; while erratics, till, or boulder clay, with certain other deposits of more doubtful origin, indicate a distribution

of materials over the lowlands directly or indirectly by the agency of ice. But in regard to these, the same difficulty is found in deciding how much is of terrestrial and how much of marine origin, how much is true till, and how much is boulder clay.

According to Professor Hull,[1] the glacial drifts of Ireland, like those of England, often exhibit a tripartite arrangement, viz., a lower and an upper boulder clay with an intervening mass of sands and gravels. Of these, the first is the most extensively distributed, and occurs in the greatest mass in the lower grounds and the deeper valleys of the country, filling up hollows and gorges, and enveloping the hill districts, becoming thinner as it rises to a height of full 1500 feet above the sea.[2] It is "a very stiff solid clay, of a dark blue or reddish colour, according to locality, and containing blocks, pebbles, and fragments of various rocks embedded therein, and in every possible position. These blocks are of all sizes, either angular or rounded," are often smoothed and striated as by the action of ice, and so are the rocks on which the material rests. On approaching the mountains, this assumes more and more the aspect of local morainic matter. It exhibits a tendency, in nearly all parts of the country, to be arranged in parallel ridges. The "Middle sands and gravels" appear to be very similar to the

[1] "Physical Geology and Geography of Ireland," chap. iv.

[2] In distribution it is somewhat irregular, certain areas, as about Inniskeen (county Louth), being free from drift, while this is thick within a distance of a few miles.

deposit already noticed in England. They consist "of stratified sand or gravel, of water-worn pebbles, sometimes of large size;" signs of current bedding are frequent, and moraine shells not uncommon. The last have been found at an elevation of 1300 feet above the sea at Caldbeck Castle, and at a rather lower level near Ballyedmonduff (where about twenty species have been collected, besides *balanus* and perforations of annelids). Near Ballycastle, in county Antrim, similar deposits occur as terraces on the flanks of the hills at an elevation of 600 feet: here they rest on Lower Boulder Clay, and appear to be overlain by a similar upper deposit.

The Upper Boulder Clay is more sparingly distributed than either of the deposits below it, perhaps because it has suffered more from denudation; but it also may be seen in many places. It apparently occurs in thicker masses than the other two deposits, attaining sometimes almost to 90 feet. In one such section (near Carlow) the "sands" were 25 feet, and the Lower Boulder Clay was only 8 feet. It consists of a reddish stiff clay, with boulders and bands of gravel or silt, sometimes showing signs of stratification, and its range above sea-level seems not to exceed 1000 feet.

When the ice-sheet attained its greatest dimensions it appears to have occupied a large part of the Irish lowland. The highlands of Galway, Donegal, and Down, the uplands of Antrim, acted as gathering

grounds from which the united masses of ice extended over Ireland nearly as far south as the mouth of the Shannon. The glaciers from the Wicklow Hills seem to have become for a time tributary to this sheet of ice, while the Knockmealdown Mountains and the highlands of Kerry formed independent centres of dispersion. The islands which fringe the coast, such as Clare Island and the Arans, are often ice-worn. The land at this time very probably stood at a distinctly higher level than at present. Professor Hull, however, considers that the main outflow of the ice-sheet took place, not from the mountainous district of the north and north-west, but from a broad strip of comparatively low land, at present not more than four or five hundred feet above sea-level, which extends, speaking in general terms, from the neighbourhood of Lough Corrib to that of Lough Neagh. But, according to the late Professor Carvill Lewis,[1] the hill region was the centre of radiation, a view which at any rate seems more in accordance with what might be expected. He was also of opinion that the north-eastern corner of Ireland had been invaded by the Scotch ice-sheet, and did not admit that the country at any time had been submerged to a greater depth than 400 feet below the present coast-line, for he considered the shells at higher levels, like those already mentioned in England and Wales, to have been scooped up from the sea-bed and transported to their present elevated posi-

[1] "The Glacial Geology of Great Britain and Ireland," pp. 83–166.

tions by land-ice.[1] But the majority of the Irish geologists believe that, after the epoch of the Lower Boulder Clay, the land gradually sank until the depression, during the time when the Middle Sands were deposited, amounted in some places to at least 1500 feet. It was then again slowly raised. The temperature, which had been higher during the submergence, again declined (though whether the fall in it was wholly due to the rise of the land is uncertain), so that glaciers once more occupied the mountain valleys, and perhaps descended sometimes to the sea-level. In short, the opinions which hitherto have been generally entertained as to the glacial history of Ireland agree in the main with those held by Sir A. Ramsay in regard to Great Britain.

In Ireland also scattered erratics occur, though they appear not to be dispersed in such regular streams as in Great Britain. They belong, in some cases, to a late stage in the history of the Glacial Epoch; but Ireland exhibits a more extraordinary series of kames or eskers than any other part of the British Isles. Groups of these extend across the great central plain from the south of Galway to the neighbourhood of Dublin, and as far north as the valley of the Laggan on the borders of Down and Antrim.[2] Near Parsonstown they are more or less

[1] The writer has seen but little of the Irish boulder clays except in counties Dublin and Wicklow. There they commonly exhibited some indications of stratification, and appeared to pass up occasionally into gravels and sands.

[2] Hull, *ut supra*, chap. v.

ridge-shaped, occasionally roughly parallel, enclosing hollows, sometimes almost circular, sometimes elongated, but now and then spreading out into knolls or shoulders. On the southern side of the broad valley of the Shannon, as, for instance, in the neighbourhood of the ancient sanctuary of Clonmacnoise, they form a line of hills in outline curiously resembling moraines. These are sometimes quite narrow at the top, but sometimes a fair breadth. Here and there an insulated hill may be seen; but generally they form a range, and occasionally the main line has a "backing" of lower mounds. The stones are mixed with fine gravel and coarse sand; they are commonly subangular to fairly rounded, ranging from about 4 to 10 inches in diameter, but occasionally much larger blocks occur, generally more angular in shape. The materials seem water-worn rather than ice-worn, and not infrequently are distinctly stratified. These hills, in short, are gravel-banks rather than moraines. In this part of Ireland most of the pebbles are a dark limestone (Carboniferous), but Palæozoic sandstones and grits also occur, with various crystalline rocks, such as a diorite and granites (reddish). Professor Sollas, who has paid much attention to these curious accumulations, informs me that the maps of the Geological Survey prove them to bear a certain relation to the general drainage system of the country, and that they converge in groups like those of stream-courses. That

they can be moraines seems impossible; it is difficult to understand how they can have been deposited either by currents in a sea or by the direct action of rivers; in short, the exact mode in which they have been formed, as already stated, is one of the unsolved problems in geology.

CHAPTER III

ICE-WORK IN EUROPE AND OTHER PARTS OF THE WORLD

THERE can be no doubt that Scandinavia, during parts at least of the Glacial Epoch, was almost buried beneath ice, but it is less certain how far southward this extended. Drifts, however, in some way of glacial origin, can be traced, speaking in general terms, to the fifty-first parallel of latitude. Some of the most remarkable sections occur in the island of Möen,[1] displayed in cliffs from 100 to 400 feet high. The chalk—like that of Norfolk—is overlain by the following deposits:—(1.) Stratified loam and sand (about 5 feet thick), containing occasionally marine shells, sometimes having a breccia of flint at the base. (2.) Unstratified blue clay, with small pebbles and fragments of Scandinavian rocks—20 feet. (3.) Unstratified yellow and more sandy clay, with pebbles and boulders (angular) from the same source—40 feet. (4.) Stratified sand and gravel, with occasional large erratics; this varies in thick-

[1] Described by Sir C. Lyell, "Antiquity of Man," chap. xvii. See also Professor J. Geikie, "Prehistoric Europe," chap. x.

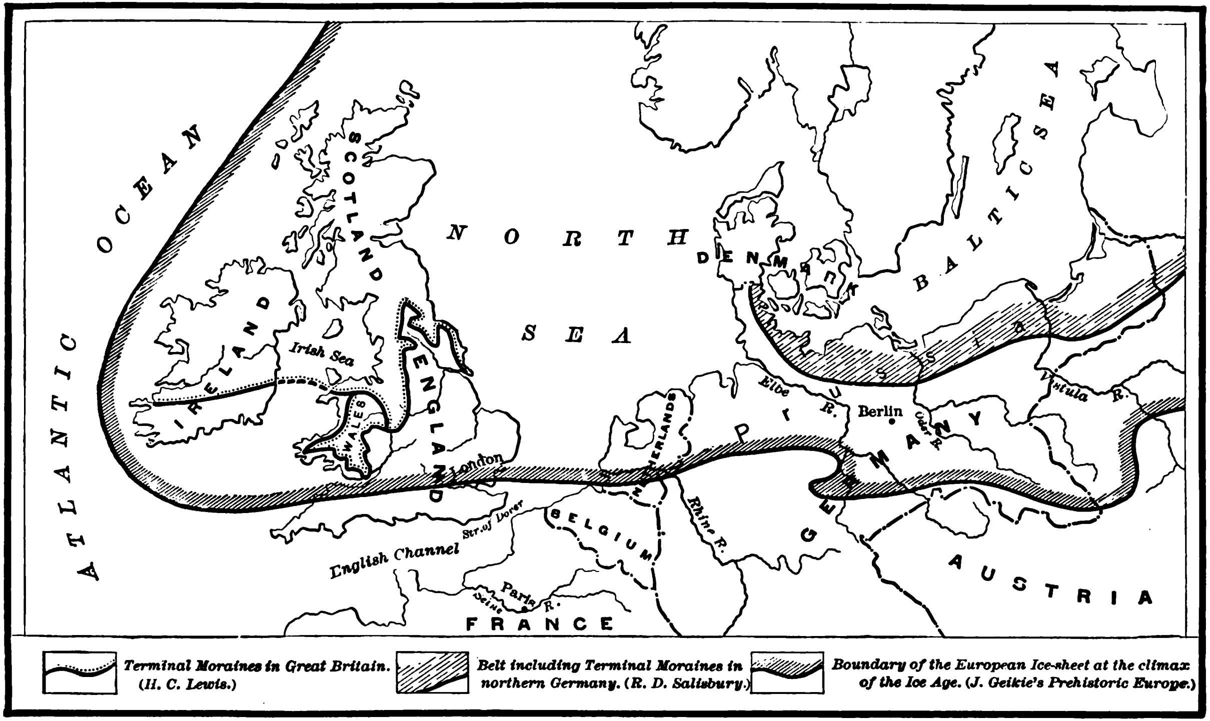


FIG. 20.—Map showing the glaciated area of Europe according to J. Geikie, and the moraines in Britain and Germany according to Lewis and Salisbury. These limits, of course, express individual opinions, but the outer one includes the deposits admitted to be directly or indirectly due to ice.

ness from 40 to 100 feet, but is local in occurrence. Here and there the Chalk and the Drift appear to have been faulted and folded together in a remarkable fashion,[1] and to have been subsequently much denuded.

Boulder clays occur abundantly, though commonly they are not well exposed, in Denmark, Holstein, and Northern Germany. They contain erratics of chalk, rivalling in size those of Cromer. Those in Mecklenburg-Schwerin are so large as to have been mistaken for rock *in situ;* but they are underlain by clay, and sometimes more than one such mass has been pierced in a boring.

Farther south, as in Halle in Saxony, deposits of brown coal (Tertiary age) are curiously mixed up with the boulder clay. This, in many districts, is parted by beds of sand or gravel, and at Potsdam at least three masses of it can thus be distinguished. In clays and sands alike, as far south as this place, marine shells can be found, sometimes also those inhabiting fresh water.[2] In fact the glacial deposits

[1] Some are of opinion that the Chalk near Trimingham (Norfolk) has been similarly bent up. I am, however, doubtful whether the mass is *in situ.* Certain geologists maintain that these disturbances are due to the uprooting and thrusting powers of an ice-sheet; but it remains to be proved, not only whether an ice-sheet ever reached either locality, but also whether ice under any circumstances can produce such effects. The hypothesis accordingly must be ranked among those which are possible, but at present are unsupported by much evidence.

[2] The clay is often extremely tough. It has been noticed that in Saxony, while most of the fragments both in it and the gravel have obviously come from the north, some undoubtedly have been derived from the opposite direction.

of this part of Europe seem to bear a considerable resemblance to those of England. The underlying rock is sometimes broken up, sometimes smoothed and striated, as is the case with the Muschelkalk near Berlin. Ice-worn or striated surfaces are said to have been observed near Wurzen in Saxony, near Halle and Leipzig, on the Rainsdorferberg, and on the Pfarrberg.

Indications of glaciers have been recognised, with more or less certainty, in the higher parts of the Black Forest and the Vosges,[1] and well-marked moraines exist in some parts of the Carpathians, as in the valleys of Biaty Dunajee and of the Theiss. In the latter, though the surrounding summits do not exceed 6800 feet above the sea, the glacier is said to have been forty-five miles long, and till with striated stones to occur as low down as 1800 feet.

Glaciers formerly existed in Central France,[2] though it is difficult to determine their exact limits. They radiated from the Puy de Sancy, and near Issoire a till has been described which is parted into three masses by gravel beds. It contains angular blocks, sometimes striated, which are often a cubic metre in volume, and occasionally even 6000 cubic metres. These have come from the Mont Dore dis-

[1] For this and the next paragraph compare the map opposite to page 35.

[2] It has been asserted that small glaciers existed in Brittany; but this appears hardly probable. Erratics, however, have been noticed, which seem indicative of some form of ice-action. (*Ann. Soc. Géol. du Nord*, 1878.)

trict, a distance of quite fifteen miles. The former presence of glaciers has been asserted, though they probably were small, on the basaltic plateau of Aubrac and Vivarais in the Cantal, and round the Puy de Dôme, also among the crests of the Menzenc and Forez hills. In the Pyrenees, as in the Alps, the ice-streams once were enormously greater than they are at present. From the northern slopes they descended on to the lowland at the base of the mountains. At the entrance of the larger valleys—as, for instance, all round the sacred grotto at Lourdes—ice-worn rocks and sheets of till may be seen; the former, with perched blocks, or lateral and frontal moraines, are common almost everywhere within the limits of the chain. The ancient glacier of the valley of the Garonne was nearly 45 miles long; that of the Ariège hardly less; that of Argelès about 33 miles.[1] The last started from a height of over 9000 feet, and the ice, at one part of its course, is said to have attained a thickness of 2500 feet. On the Spanish side of the chain the glaciers were less extensive, but they attained a considerable size in the Cantabrian mountains.[2] Erratics and other traces of ice action have been also found in the Sierra Guadarrama (10,551 feet) and in the Sierra Nevada (11,678).[3]

[1] E. Trutat, *Les Pyrénées*, pp. 72–102.

[2] The highest summit of this chain is 10,910 feet; but this is exceptional. The peaks are generally under 8000 feet.

[3] The present level of the snow-line in the Pyrenees is about 9000 feet, and in the Sierra Nevada about 9500 feet.

The Alps have been already noticed. The Maritime Alps of course had their glaciers, when the more northern part of the chain was swathed in ice, and so had the mountains of Istria and Dalmatia. Moraines occur in the Apuan Alps, and traces of glaciers have been noticed in other parts of the Apennines—as in the corries under the peaks of the Gran Sasso d'Italia (9557 feet), in the valleys of the Arni and Serchio, and about Monte Majella. They have been found also in the mountains of Corsica. The moraines and other traces of a small glacier may be seen, at a height of about 6000 feet, at the head of the valley of the Golo, to the east of the group of peaks between the Col di Vergio and Col di Guagnerola. There are ice-worn rocks at a level of about a thousand feet lower in a valley leading up to the south-west base of the Monte d'Oro (8704 feet). In fact, the higher peaks of the island, which rise from rather below eight to just above nine thousand feet from the sea-level, seem formerly to have resembled the Cottian Alps at the present time.[1]

Deposits generally similar to those of Northern Germany extend over Russia as far south as the 50th parallel of latitude on the western side of the country. Moraines and erratics have been found in the Ural range at about the 57th parallel. Siberia, as a rule, is without glaciers, even where the ground is per-

[1] I am indebted for some of this information to D. W. Freshfield Esq., F.R.G.S.

manently frozen to a very considerable depth, for the amount of precipitation is too small to admit of the accumulation of snow; but the parts of the higher plateaux which rise above 2000 feet from the sea-level in the north, above 3000 feet to the east of the Lake Baikal, 5000 feet in the middle part, and to a yet greater elevation (the exact amount not being at present precisely known) farther south, show traces of a general glaciation.[1]

But in the great mountain chains of Central Asia, the summits of which often rise above 20,000 feet, and even range up to 29,000 feet, huge glaciers are still abundant. The height of the snow-line[2] and the extent of ice, as might be expected, differ much. To take one district as an example: the extreme length of the glaciers in the Karakoram Himalayas, where many peaks range from 22,000 to 28,000 feet, is about forty miles. To this distance, for example, the great Hispar Glacier descends, the "col" at its head being 17,650 feet above the sea. The glaciers do not now come down lower than about 10,000 or 10,500 feet, but traces of ancient ice-streams may be found, often abundantly, down to about 5500 feet, and possibly beneath this.

The snow-line in the Caucasus ranges from 9500 feet at the western end to 12,200 at the eastern, and

[1] Kropotkin in *Nineteenth Century*, 1894, p. 146.

[2] The Karakoram Pass, about 20,000 feet, is almost free from snow, but farther west this appears to descend nearly to 15,000 feet.

the glaciers in the central part not very infrequently terminate at between 7000 and 8000 feet above sea-level. Two on Elbruz and one on Kasbek come within this zone. The Karagam Glacier (about the length of the Great Aletsch in the Alps) ends at 5700 feet, and descends lower than any other on the northern side.[1] On the southern, Leksur descends as nearly as possible to the same level, but it is passed by Chalaat, which reaches 5180 feet.

The snow-line on Ararat is at about 14,000 feet, and its glaciers end at about 12,500 feet;[2] but they had formerly a greater extent. Moraines exist at a height of about 6000 feet above the sea in the Lebanon, where the crests of the range rise up above 8000 feet, and the highest summit attains 10,200 feet; on it the snow remains in patches throughout the year. On Hermon also (9400 feet) traces of glaciers are said to be visible.[3] In Sinai none have been discovered.

Gigantic boulder-beds flank the northern escarpment of the Atlas Mountains south of Morocco, spreading down in great mounds and undulating ridges from a height of 3900 feet above the sea to the level of the plain (1900 feet), and extending up the lateral valleys as well-defined and symmetrical moraines. These also—in some cases of great size—are found

[1] D. W. Freshfield, *Alpine Journal*, xii. 320.
[2] Parrot, "Ararat," chap. xi.
[3] Tristram, "Land of Israel," p. 607.

near the heads of the principal valleys, beginning at a height of about 5800 feet, and extending up to between 7000 and 8000 feet above sea-level; the neighbouring peaks rising from 12,000 to 13,000 feet.[1] The glaciers of Mount Kenya (19,500), which now terminate from 15,300 to 15,600 feet above the sea, once came down, according to Dr. Gregory, 5400 feet lower;[2] but those of Mount Kibo, so far as has been ascertained, have not been more extensive than at present. It would be interesting to ascertain whether the same holds good of Kimaweenzi, which is evidently much the older peak.[3]

This summary, necessarily much condensed, may suffice to show the general condition of the Old World region of the Northern Hemisphere at the present time and during the Glacial Epoch, though the evidence as regards the latter may not always be of equal value. In some instances, the remains of mud avalanches may have been mistaken for morainic deposits, or the indications of glaciation may have been too readily recognised; but, making every allowance for these sources of error, we seem justified in concluding that the temperature of no small part of this hemisphere was once considerably lower than it is at the present time, and that very probably the region was affected

[1] Maw, *Quart. Jour. Geol. Soc.*, xxviii. (1872), p. 85.

[2] *Quart. Jour. Geol. Soc.*, l. (1894), p. 515.

[3] Mr. Scott Elliot (*Nature*, Jan. 17, 1895, p. 271) states that on Ruwenzori glaciers appear to have extended seven to eight miles down two of the valleys, but that he saw no signs of extensive glaciation.

as a whole, that is, by a cause which was general rather than local.

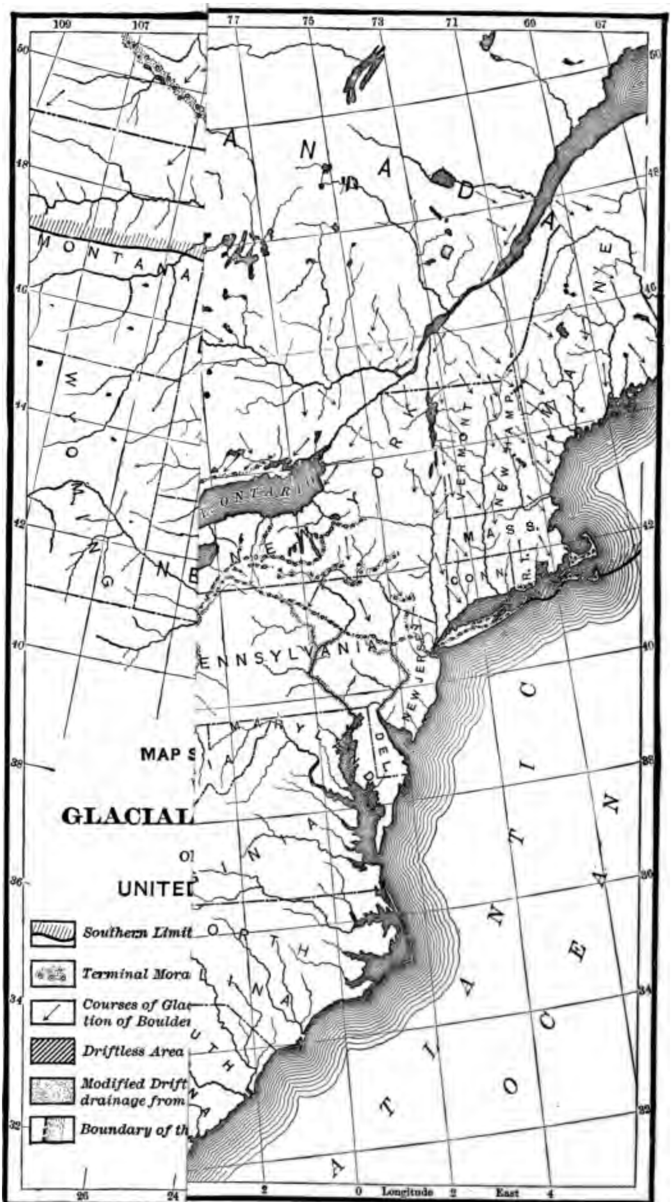
Not a few excellent descriptions have been written of the glacial phenomena in North America; but here, as in Great Britain, much difference of opinion still exists in apportioning the work of land ice and of floating ice. In many localities there can be no doubt that the former, as in Switzerland, was practically the sole agent; but in others a submergence, at any rate for a time, is equally certain, so that the difficulties of interpretation are very similar to those with which we are familiar in Britain and the adjacent parts of Europe. It is also a matter of dispute whether two episodes of severe[1] cold were separated by one when a milder temperature prevailed, or whether there was really but one continuous epoch of glaciation.

But, notwithstanding these difficulties, many facts are generally admitted, of which the following seem the most important:[2]—The striated surfaces made by moving ice are found abundantly in Canada and in

[1] Some authors even think that there were three ice invasions, the last being the least important, and the first rather greater than the second.

[2] For fuller details we refer to another volume of this series, Dr. Wright's "Man and the Glacial Period." The number of books and papers dealing with the subject is now very great, but for useful summaries with further references we may mention T. C. Chamberlin in the Seventh Annual Report of the U.S. Geol. Survey; G. M. Dawson in *Proc. Roy. Soc. Canada*, vol. viii.; Sir W. Dawson in "The Canadian Ice Age;" and G. F. Wright, "The Ice Age in North America." It must be remembered that these authors do not all agree in the interpretation of the facts.

the United States. In the latter, Professor T. C. Chamberlin, writing in 1886, states that 2500 observations have been made, of which nearly one-fourth occur in New Hampshire. The great majority of these marks lie on the northern side of an undulating boundary, which begins a little south of New York city, and runs inland for a considerable distance in a W.N.W. direction. On approaching Lake Erie it turns rather sharply to the S.W., till it comes down nearly to the 39th parallel of latitude. After passing below the southern end of Lake Michigan it turns north, retreating within the 45th parallel near the western end of Lake Superior. Thus a considerable district, drained by the upper part of the Mississippi, is free from striations. Before long, however, the ice again encroaches southwards, and its boundary extends in two great lobes into Iowa and the north of Nebraska. Thence it passes away northwards through Dakota into Canadian territory. Between the 83rd and 97th parallel of longitude another and outer boundary-line is drawn, which generally runs to the south of the 39th parallel of latitude, going in one place, between the Ohio and the Mississippi rivers, nearly a hundred miles beyond it. Within this second line striations have been found, though less commonly. Like the other one, it turns northward, but does not cross the frontier of the States. This line is considered by many geologists to indicate the limit of an earlier and more



MAP S
GLACIAL
O
UNITED
Southern Limit
Terminal Mora
Courses of Glac
tion of Boulder
Driftless Area
Modified Drift
drainage from
Boundary of th
C A N A D A
MONTANA
W Y O M I N G
N E B
NEW YORK
ONTARIO
PENNSYLVANIA
NEW JERSEY
MARYLAND
DEL.
VIRGINIA
NORTH CAROLINA
SOUTH CA
VERMONT
NEW HAMPS.
MAINE
MASS.
CONN.
R.I.
ATLANTIC OCEAN
Longitude
East

extensive glaciation. The centre of the ice-sheet (regarding the two as connected) lay to the north of the river St. Lawrence. This highland region then formed—like Greenland at the present time—a vast gathering-ground from which ice radiated in all directions, though less is known of its northern slopes towards the barren shores of Hudson Bay and Strait. Simultaneously the Cordilleran region of Canada—the Rocky Mountains and the ranges between them and the Pacific—became the focus of another ice-sheet. "Eventually the greater part of the region became covered and buried either in névé or beneath glacier-ice." Ultimately the Cordilleras, "between the 48th and 63rd parallels, or for a length of about 1200 miles,[1] seem to have assumed an appearance closely analogous to that of Greenland at the present day, save that in consequence of the high bordering mountain ranges, with the general trend of these and of the lower intervening country of the Interior Plateau, the greater part of the ice was forced in this case to follow its length in the directions above indicated, instead of discharging laterally on both sides to the sea;"[2] to which, however, a certain proportion of the ice made its way through passes in the Coast Range, reaching the shore of Queen Charlotte Island and crossing the coast archipelago on the south-east side of Alaska.

[1] The average width being about 400 miles.
[2] G. M. Dawson, *Trans. Roy. Soc. Canada*, viii. (1890), p. 27.

At this time the Cordilleran region was nearly a thousand feet (possibly even more) higher than at present, but the eastern plains were rather lower. The eastern margin of the Cordilleran ice-sheet, at the period of its maximum extension, came in places near to the western one of that from the Laurentide region; but whether these periods were synchronous or the two areas actually joined is open to question.

As the ice retreated, it often left moraines to mark its halts, and the land generally[1] is covered with sheets of stony glacial deposits of variable thickness, which sometimes filled valleys and blocked up glens. Erratics can be found which in some cases are nearly six hundred miles away from the parent rock, and are perched not seldom some hundreds of feet above it. The same diversity of opinion as to the history of these clays with boulders exists in America as in England. Some authorities consider them to be almost wholly the product of land-ice—the ground moraine of the retreating glacier, augmented by material either incorporated into the ice itself, or carried upon its surface. Others think that, though mainly produced by the action of ice, they have generally been deposited under water. Both parties agree that in some cases streams running in the direction opposite to that in which the ice was advancing might be dammed up till their valleys were

[1] There is a singular driftless area in Wisconsin and parts of the adjacent States. See Wright, "Man in the Glacial Period," p. 101.

converted into lakes; but the second school of geologists asserts that whatever greater elevation the land may have had at the outset, this was followed by a subsidence sufficient to bring a considerable part of the lowland region beneath the level of the sea.

Scattered erratics, often of great size, occur in this American region, and sometimes form trains as in England. Kames in some districts, as in Maine and the south-eastern part of New Hampshire,[1] seem to be no less wonderful than in Ireland. So far as I can judge from the evidence published,[2] and from the few sections which I have seen, the glacial phenomena of North America often resemble those of Great Britain, only they are generally on a more gigantic scale. Some of the glacial clays containing erratics, like the tills of Switzerland and of Britain, must be in some way or other the produce of land-ice. Here and there also intercalated beds of peat or of other vegetable matter indicate a retreat, and a subsequent return, of the ice-sheets. But in other places the boulder clays either show signs of stratification or pass up into stratified silts, sands, and gravel. These in some cases may have been deposited in extra-morainic lakes, but in others they must be of marine origin. Of the latter there are many proofs, but

[1] "Man and the Glacial Period," pp. 77–81.

[2] Especially in the reports of the U.S. Geol. Survey, which contain numerous admirable reproductions of photographs representing the various phenomena.

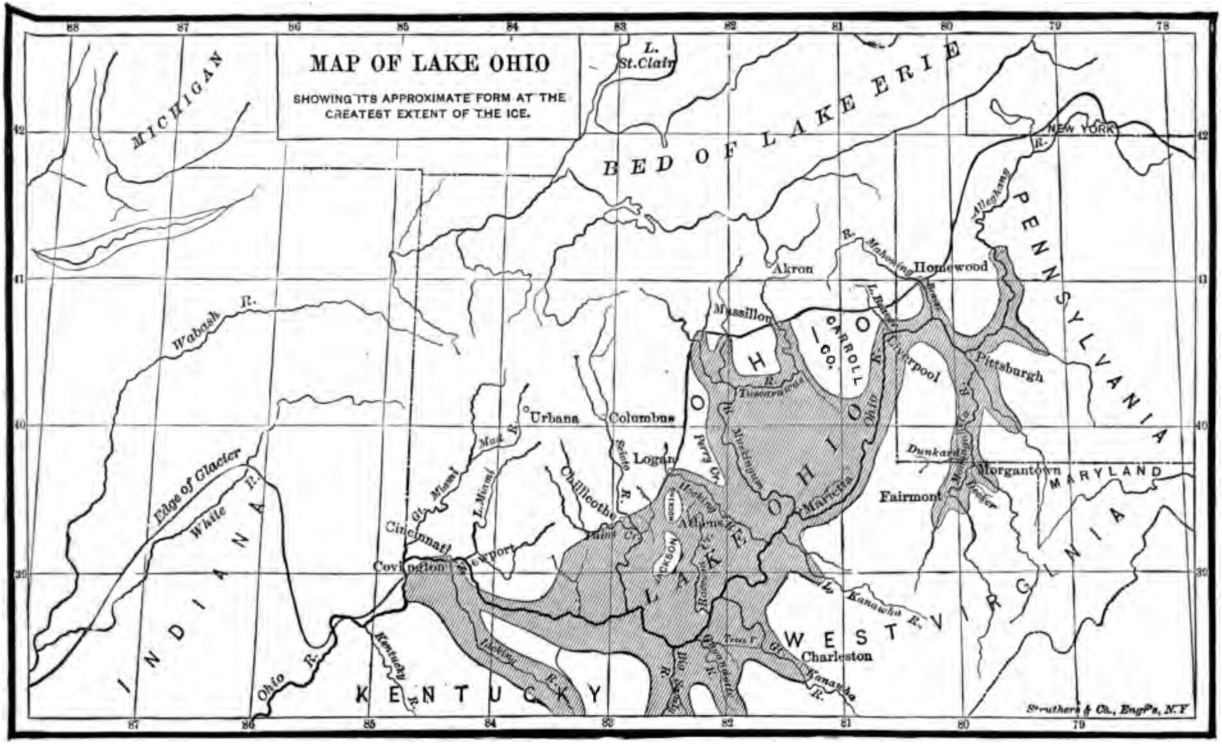


FIG. 22.—Map showing the alleged effect of the Glacial Dam at Cincinnati. (Claypole.) (*Trans. Edinb. Geol. Soc.*)

it may be sufficient to quote a single instance. On the flanks of Mount Royal, at a height of nearly five hundred feet above the sea, the surface of the Ordovician limestone, when uncovered in the process of quarrying, is often found to be smoothed, polished, and striated. This is no local or accidental phenomenon, so that it can hardly indicate anything but the passage of an ice-sheet. That surface is covered by boulder clay containing blocks of similar limestone, of the Laurentian gneisses, and of gabbro from the so-called Norian System, above which comes, apparently without any marked break, another clay containing *Yoldia* (*Leda*) *arctica*, which is overlain by the Saxicava Sand,[1] a stratum full of marine mollusca. In this position, far away from the present estuary of the St. Lawrence, it is impossible to appeal to any scooping up and transference of material from the Atlantic sea-bed; the moulding also of the rock surface and the direction of the striations show that the ice came from the Laurentide hills, and not up the Gulf of St. Lawrence. In other parts of North America, even in the neighbourhood of the Cordilleran ice-sheet, beach terraces occur. Some can be proved

[1] A list of the fossils from the Leda Clay and Saxicava Sand is given by Sir. W. Dawson, "The Canadian Ice Age," pp. 211–268. Bones of *Phoca Grœnlandica*, *Beluga catodon*, and *Megaptera longimana* have been found in these or similar deposits at Montreal or far inland; the last at an elevation of 440 feet above sea-level. The marine mollusca occur frequently on Mount Royal up to 470 feet, and they have been found in one place at 500 feet. Sir W. Dawson, *op. cit.*, p. 199.

by the presence of molluscs to be of marine origin, but others may possibly be lacustrine, and may mark the shores of those inland sheets of water which were produced by interruption of the drainage system of the country (Fig. 22). There can be little doubt that in Northern America such lakes have been more important factors in the production of stratified drifts, especially of the finer clays, than in our own country; and the fact of considerable oscillation of level, even since the Glacial Epoch, appears to be proved by the observations on the heights of the old shore-terraces in the region of the great lakes.[1]

Outlying glacier systems of course existed in favourable situations in the great mountain regions far to the south of these two main centres of ice dispersion, but it is needless to do more than mention them. There can be no doubt that for a considerable time the temperature of a large portion of North America was materially lowered, while the amount of precipitation apparently was not diminished, so that ice-sheets, originating from the two districts already mentioned, trespassed upon the lowlands. But though the evidence of their presence here is indubitable, that of marine action in some regions seems to be no less certain. Accordingly, it often becomes difficult to assign the glacial deposits to

[1] There is an important paper on this subject by W. J. McGee, "Pleistocene History of North-Eastern Iowa," in the Eleventh Annual Report of the U.S. Geological Survey, part i. See also Professor J. W. Spencer, *Quart. Jour. Geol. Soc.*, xlvi. (1890), p. 523.

their true origin. It is also no less difficult, with

FIG. 23.—Map showing Old Channel and Mouth of the Hudson. (Newberry.)

our present knowledge, to determine how far climatal changes during the Glacial Epoch were the results

of elevation or depression of the surface, and how far they were due to more general causes. Both the maximum cold and the greatest elevation of the land appear to have characterised the earliest part of the epoch, and to have been followed by a subsidence and a less severe climate; but as the land again rose the ice increased, seemingly to a larger extent than could be attributed to this movement alone; and even since it melted for the second time there have been important changes of level. In short, the last chapters in the physical history of North America and of Great Britain appear to exhibit a general correspondence, and the record of the Ice Age in both presents very similar difficulties of interpretation.

In the Alps of New Zealand, as in those of Switzerland, are snow-clad peaks and important glaciers. The centre of the system is Mount Cook or Aorangi, in latitude 43° 30′ S., which rises to a height of 12,349 feet. The snow-line lies from 2000 to 3000 feet lower than in Switzerland;[1] much the same is true of the ends of the glaciers. On the eastern side of the range the Hooker Glacier terminates at 2882 feet, the Mueller Glacier at 2500 feet, while the great Tasman Glacier comes down to 2354 feet. The former has a length of eight miles, but the latter, the largest in the country, is eighteen miles long, and

[1] The supply-basins of glaciers are correspondingly lower, their heads often lying between 5300 and 8600 feet.

on the average rather more than a mile wide. On the western side the glaciers reach a still lower level, for the slopes of the valleys are steeper and precipitation is heavier.[1] Two of them descend nearly to 1200 feet, and the Fox Glacier even as low as 700 feet, tree-ferns growing almost on its terminal moraine. The most rapid motion of the ice that has been observed slightly exceeds a foot a day. The glaciers have diminished greatly in size since a date which, geologically speaking, is quite recent. The old lateral moraines are very marked, being sometimes as many as five in number on the flanks of the Hooker Glacier; the path of the ice can be followed down the valleys, and "on the Mackenzie plain one rides for upwards of forty miles through ancient terminal and lateral moraines." These, in South Canterbury, are found at about 1000 feet above sea-level, and yet lower in South Otago, where they come down to 600 feet. More than one of these old glaciers exceeded fifty miles in length, and Wakatipu reached eighty miles. The ice formerly had its greatest extension in Central Otago, but now it is at a maximum in South Canterbury.[2] Boulder clays, however, apparently, do not occur, and the character of the New Zealand flora is opposed to

[1] The rainfall at Hokitika, on the west coast, is 118 inches; at Christchurch 25 inches. G. E. Mannering (New Zealand Alps, p. 120) says it amounts in some places to more than 150 inches.

[2] Report of Australian Association, summarised in *Nature*, vol. l. p. 483.

the idea that the climate of the islands, in times comparatively recent, can have ever been very severe.[1]

No signs of general glaciation have been observed in Australia, but Dr. R. Von Lendenfeld found *roches moutonnées* and moraines in the highest parts of the Australian Alps, where the peaks range generally from 7000 to 8000 feet, the lowest limit of the traces being 5800 feet above sea-level. When these were formed, the condition of the region must have resembled that of a part of the European Alps, where the peaks range from about 9000 to 10,000 feet.

Tasmania is a mountainous island, the summits often rising from 4000 to 5000 feet above the sea-level, but very few exceeding the latter amount. Lakes, one being fifty miles round, lie at a high level in the valleys which run northwards from the centre of the island, and the more elevated hills occur generally on the western and southern sides. Moraines, *roches moutonnées*, and other traces of glacial action have been found in the western portion of the island, but are absent from the central valley (the lake region) and the eastern side. Polished and striated rocks have been detected within about 25 feet of the summit of Mount Tyndall (3850 feet), from which it is inferred that the great central plateau at a height of about 4000 feet must have

[1] See the statements of New Zealand geologists, collected by Sir H. Howorth, "The Glacial Nightmare and the Flood," pp. 484–488.

been buried deep in ice or névé; no traces, however, have yet been discovered beneath the level of 2000 feet, and the Tasmanian geologists are of opinion that this was the lower limit of the ancient glaciers.

[1] *Nature*, vol. xlix. p. 3.

PART III

THEORETICAL QUESTIONS

CHAPTER I

TEMPERATURE IN THE GLACIAL EPOCH

An attempt to ascertain the temperature of North-Western and Central Europe during the Glacial Epoch seems at first sight unpromising, because much depends on the extent of the ice-sheets, a matter on which great diversity of opinion exists. Nevertheless we may find that one district throws light on another, and that an instance, where the evidence is clear, may be used to test results or supply a standard for places more open to doubt. It must be remembered that the size of an ice-sheet depends upon the amount of precipitation quite as much as upon the lowness of the temperature, so that the answer to the question which would be accepted by one party might fairly satisfy the other. Perhaps also the diversity of opinion as to the origin of a boulder clay does not indicate anything like a corresponding difference as to the mean annual temperature at the time when it was formed. For suppose it be attributed to the action of floating ice: that requires the winter to be very cold, which might be counterbalanced by a warmer summer; while a temperature generally low

but less extreme probably would be more favourable to the formation of an ice-sheet. In other words, a phenomenon continental in character is most favoured by a rather insular climate, and *vice versâ*. Thus, whichever of the opposing views be correct, it may suffice for our present purpose to attempt to determine approximately the mean annual temperatures, which cannot have been exceeded during the colder part of the Glacial Epoch, and it will be enough to ascertain this for a few localities, since the general principle will apply in all.

In the first place, let us assume that the glaciers of Wales came down at least to the present sea-level, that Scotland and Norway resembled Greenland, though on a smaller scale, and that the Swiss lowland was buried deep under ice. These assumptions are not likely to be disputed by either school of geologists; for those who are advocates of a submergence in North-Western Europe admit that, prior to it, the ice had something like this extension.

At the present time the snow-line in the Central Alps corresponds approximately with the contour of 8000 feet, and with a temperature[1] rather below the freezing-point, say 30° F.[2] Glaciers of import-

[1] Henceforth the word "temperature" is to be taken to signify "mean annual temperature," unless it be otherwise specified.

[2] The exact height of the snow-line, that is, the level above which the "income" due to precipitation in a solid form is not exhausted by the "expenditure" demanded by heat, is not the same in all parts of the Alps, and depends to some extent on the aspect of the place, the nature of the rock, &c.; but these only produce minor variations.

ance rarely form unless the "feeding-ground" is at least a thousand feet higher than the snow-line, that is to say, its temperature is not above 27°.[1] Again, in Greenland the temperature is slightly over 32°[2] at the southern extremity, and it declines to about 18° in latitude 70° on the western coast. In other words, an ice-clad region is not likely to exist where the temperature comes within 5° of the freezing-point.[3]

Suppose, then, that the temperature of the Snowdonian region were lowered from 50° (its present amount at the sea-level) to 30°. Then the snow-line would correspond with the margin of the land, and the feeding-ground of glaciers should begin a thousand feet above it. This change should suffice to make the mountains of North Wales like the Oetzthaler peaks in Tyrol from the snow-line upwards, and to bring their principal glaciers down to the sea. If, however, the land, instead of maintaining its present level, were elevated 600 feet, with a temperature of 32° at the new sea-shore, the ice might then extend to some distance from the mountains, though possibly the glaciers would hardly be large enough to become confluent.

The mean temperature of the Cumbrian region

[1] For details see an article by the author in the *Contemporary Review*, 1891, p. 716.

[2] Lichtenau 33.98°; Iviktut 32.90°.

[3] The temperature of the hill country of Southern Greenland, where the glaciers form, is of course some degrees below 32°.

is about a degree and a half lower than that of Carnarvonshire, and the shape of its mountains is perhaps a little more favourable to the accumulation of snow; hence a fall of 20° should surround them with yet larger fields of ice. The temperature of the Western Highlands ranges at present from about 46° to 48°; by the same change it would be reduced to from 26° to 28°. These correspond with the results which have been obtained for the coast about Godthaab in Greenland (latitude 64° 10′). "The Highlands then would be enveloped in a winding-sheet of ice, broken only here and there, except in the neighbourhood of the coast, by some solitary crag." The temperature of the western margin of Scandinavia now ranges from about 43° to 33°; if these figures are reduced by 20°, they correspond roughly with the temperature of West Greenland from Jakobshavn to Upernavik. Accordingly we seem justified in inferring that a fall of temperature amounting to 20° would suffice to produce very great glaciation in Britain and Scandinavia.[1]

[1] If the land in Britain, during part of the Glacial Epoch, stood at a lower level than at present, and if erratics were transported and boulder clay was formed by the action of shore-ice, the actual climate could not be less severe. For instance, if North Wales were depressed 1000 feet, the feeding-ground of glaciers would then begin at the present line of 2000 feet, and the resultant ice-streams would be only small. For shore-ice to become an important factor in transportation the temperature at the sea-level probably would have to be below 30°, unless the winters were very severe (or, in other words, unless continental rather than insular conditions prevailed). So, even if the advocates of a submergence are right, the actual variation of

In the case of the Alps, the present temperature of the Swiss lowland is about 47°, and that of the Piedmontese plain not higher than 54°. A reduction of 18° would bring down the one to 29° and the other to 36°. This ought to be quite sufficient, because on the one side all the mountain region above the 2000-feet contour-line—for example, the whole valley of the Reuss above Gurtnellen on the Gothard Road—would become a feeding-ground of glaciers; on the other side this would be the case with everything higher than Pré St. Didier (or a contour-line about 1700 feet above Aosta). By a reduction of 15° instead of 18°, the margin of the supply region would be raised 900 feet, and the temperature of the lowland would be about 32° in Switzerland, and 39° on the Italian side. This possibly might suffice; for the larger glaciers of the Alps at the present time come to an end where the temperature, speaking in general terms, is about 43°. Here, however, they descend a much more rapid slope than they would find in the lower part of the valleys, so that they may perhaps be able to reach a warmer zone than an ice-sheet with its longer journey would do; but against this there would be a set-off in the rapid increase of the supply-ground as the temperature declined.

climate during the Glacial Epoch may have been but small, the apparent variations being produced by alterations in the level of sea and land.

On the northern slope of the Pyrenees the snow-line at the present day lies generally rather over 9000 feet above sea-level (from 9186 to 9515 feet). The temperature at Pau (620 feet) is 62°. A reduction of 15° would bring this down to 47°, and the snow-line nearly to 4500 feet, which, under existing conditions of precipitation, might suffice to produce glaciers large enough to trespass upon the lowland.

We proceed to regions in Europe from which the glaciers have disappeared. The mean height of the Schwarzwald is given as 2100 feet for the part north of the Kinzigthal, the highest summit reaching 4480 feet; and the mean height of the more southern region as 3100, with a maximum elevation of 4780 feet. The Grandes Vosges average 3000 feet, and the highest point is 4680 feet. The temperature at the sea-level in this part of Europe should be from 51° to 52°.[1] Assuming the latter, it should now be 45° at 2100; hence a reduction of 15°, supposing other conditions favourable, might permit the formation of small glaciers in the Schwarzwald, for then the temperature at 3000 feet would be 27°, while in the Vosges they would be somewhat larger. In either case a reduction of 18° should make the latter range, at about 3000 feet, bear some resemblance to such a region as the part of the Lepontine Alps which encloses the Binnenthal.

As the temperature at Madrid (2150 feet) is

[1] At Ulm (1553 feet) it is 46.76°; at Strasbourg (468 feet) 50.36°.

56.3°, that at 8000 feet in the Sierra Guadarrama should be 37°. A reduction of only 15° should bring this down to 22°, which ought to allow glaciers to form; and the same should hold good for the Sierra Nevada. A like reduction would make the temperature of Gibraltar 48° instead of 63°, or about 40° on the upper part of the Rock. As this amount is just half-way between the present records for Christiania and for Bodö in Norway, the winter snowfall might be sufficient to produce the massive breccias which often cover its slopes.[1] The temperature at Ajaccio in Corsica is now 63.68°, or about 40° at 7000 feet; a reduction of 15° would bring back small glaciers among the higher summits: and the same should suffice for the Gran Sasso d'Italia, since the present temperature at the height of its peak should be 36°. In the Atlas Mountains the present temperature at 7000 feet is probably 44°; if this were reduced to 29° the glaciers in the region mentioned in a former chapter ought to be at least as large as those which now exist in the Bernese Oberland.

At the present time the snow-line in the Caucasus ranges from 9500 feet at the western end to 12,200 feet at the eastern; this, by a reduction of 15° of temperature, would be brought 4500 feet lower, with a corresponding increase of the glaciers.[2] It is

[1] A. Ramsay and J. Geikie, *Quart. Jour. Geol. Soc.* xxxiv. (1878), p. 505.

[2] It must be remembered that the Caucasian peaks considerably overtop those of the Alps. This generally compensates for the greater elevation of the snow-line.

needless to pursue the subject further. A reduction of 15°, or at most of 18°, ought to bring back a large area of Europe and the district around the Mediterranean to the condition which prevailed in the Glacial Epoch, though perhaps it would be hardly sufficient for the British Isles.

In regard to North America, the temperature in the region of the Great Lakes (except Superior) now ranges from 42° to 48°, that of Quebec is about 39°, and in the district where the end of the great ice-sheet is generally placed by the geologists of that continent it is about 56° (slightly higher than that of the Piedmontese plain). A lowering of 15° would reduce the last to 41°, and bring the temperature of the other districts into almost exact correspondence with those of West Greenland from Iviktut on the south nearly to Jakobshavn on the north. By this reduction all the hill-country of Canada would become a feeding-ground, and it should produce, assuming a sufficient amount of precipitation, an ice-sheet large enough to extend into the warmer lowlands. A reduction of only 12° would replace the forts of Quebec by an ice-cap, and convert the Laurentide hills into a great nursery of glaciers; and as the feeding-ground is so large, it is possible that the ice might not finally melt till it reached a temperature above 44°.

In the Straits of Magellan at the present day the temperature is about 42° or 43° F., and the snow-

line lies at about 3000 feet, at any rate on the mainland side, where the mountains rise to a greater elevation. Those in Tierra del Fuego or the other islands attain in one or two cases to about 7000 feet, and glaciers occasionally descend to the sea. The same thing happens in Beard Island, the highest point of which also rises to this level. Ice evidently once occupied a larger area, but, so far as I am aware, its precise limits have not been ascertained. At the present time the temperature of these regions is seven or eight degrees below that of parts of England in corresponding latitudes. The southern portion of the South American continent is evidently a "sunk country." Hence an elevation of about a thousand feet would considerably augment the volume of the glaciers, and the actual climatic changes which this region demands appear to be comparatively small.

New Zealand at the present day enjoys a temperature rather higher than that of England. In Dunedin, about latitude 46° S., or rather south of the higher mountains, it is 50.7°, and in Southland, on nearly the same parallel, 50.4°, while in Christchurch, very slightly north of the latitude of Aorangi, it is 52.7°. Thus, if 52° be taken as an average sea-level temperature at the base of the higher peaks, and the snow-line be placed at 6000 feet—corresponding with a temperature of 30°—this would imply that the thermometer falls on an average about 1°

for each 270 feet, and would give an approximate temperature of 43° at the end of the glaciers on the eastern slopes, or one not very different from that of similar positions in Switzerland. But, so far as one can discover, the ancient glaciers of New Zealand appear to have been less extensive than those of Switzerland during the Glacial Epoch, and might not have required the snow-line to have descended more than about 2000 feet, or the fall of temperature to have been more than 8°, which would reduce that of Christchurch to 44.7°. It is indeed possible that a fall of 6° might suffice. But the mountains may once have been higher, for the outline of the coast is indicative of some submergence, so that the "Glacial Epoch" of New Zealand might be the result of very slight climatal change.

The Australian glaciers evidently were never large. The facts mentioned on p. 226 suggest that formerly a temperature of about 27° may have existed at 7000 feet. It is now 62.7° at Sydney, about half a degree higher at Adelaide, and nearly 57.5° at Melbourne, so the sea-level temperature in the latitude of Mount Kosciusko is probably about 61°. Supposing the rate of fall to be as in New Zealand, the temperature at 7000 feet should now be 35°. If so, the temperature in Glacial times must have been at least 8° lower than at present, or we have to choose between this amount of climatal change and an elevation of the land not less than 2000 feet.

In Tasmania the record for Hobart Town is slightly under 56°, but the island as a whole lies between the isotherms of 50° and 55°, so that 53° is probably a fair estimate for the central part. Though the glaciers apparently did not descend below about 2000 feet, the ice seems to have been fairly thick and extensive at 4000 feet. At that time the latter altitude may have corresponded with one of 10,000 feet in the Alps at the present day, or with a temperature slightly above 23°. It must now be 40°, with the slower rate of fall of 1° for 300 feet,[1] or 38° for the more rapid one of 1° for 270 feet. Tasmania accordingly seems to demand a more marked climatal change than New Zealand, or a fall of temperature not less than 15°; but as its outline also suggests a comparatively recent subsidence, the actual alteration need not have exceeded 13°, and possibly may have been rather less. Still, on the whole, Tasmania, like Australia, suggests a rather more marked climatal change than New Zealand.

To conclude, the Southern Hemisphere indicates a comparatively recent glaciation, which, as in the Northern one, produced a more marked difference in the more temperate regions. So far, however, as our knowledge goes, the change of climate need not have been very great. The amount of this, if we could reason from New Zealand, which is not much smaller, though more insular in situation, than the British

[1] The one which we have generally adopted.

Islands, would be less than one half that which the latter require; but the height of the New Zealand Alps must cause their glaciers to increase more rapidly with changes of climate, and thus makes the comparison unfair, so that probably Tasmania affords a safer standard. Hence the change may have been about three-fifths of that required in Western Europe. In this region, however, the temperature is raised to an abnormal height, for the latitude, by the warm currents of water and air from the Atlantic, so that it would be greatly lowered by the diversion of these, and this might be the result of changes only geographical. To what extent the climate of Western Europe would be affected by the severance of the Isthmus of Panama and the union of Florida with Cuba is a matter of dispute, but it could not fail to be considerable.

The extension of the glaciers on Mount Kenya (19,500 feet) is specially interesting, because its position (almost on the equator) suggests a possible refrigeration of the earth as a whole rather than of its hemispheres alternately. Formerly, as already stated, its glaciers descended to a height of about 9800 feet above sea-level, or their end was about 9700 feet vertical beneath the summit, instead of about 4000 feet, as at present. Kenya, in those days, must have presented conditions generally corresponding with those of a peak in the Alps rising to a height of about 14,000 feet (where the snow-

line is about 8000 feet, or 6000 below the summit). On Kenya formerly this line should have been not far from 13,500 feet above the sea, and its present level must be about 15,000 feet; a difference which roughly corresponds with a lowering of temperature amounting to 5°.[1]

Other instances might be given, but as the results would be similar, it is hardly necessary to cite them. They seem to justify the following inferences:—

(1.) That in districts where the present temperature is abnormally high—as on the western coast of Britain—a fall of not less than 20° may be sometimes requisite, but that in more normal regions (in the Northern Hemisphere) one of from 12° to 15° is generally sufficient. (2.) That in the Southern Hemisphere a less reduction is generally demanded. (3.) That in some of the instances which have been quoted the reduction in temperature cannot have exceeded (supposing other conditions unchanged) the estimates given above, because in such case glaciers would have been produced larger than those which the moraines and other traces prove to have existed. From this it follows that districts where the glaciers have never been other than small are better guides in any attempt to estimate the temperature of their

[1] Dr. J. W. Gregory, the explorer of Kenya, is, however, more favourable to the idea that the refrigeration was produced by an uprising of the region, and not by any general climatal change. *Quart. Jour. Geol. Soc.*, l. (1894), p. 526. Perhaps the estimate made of the change of temperature given above may prove to be slightly too small.

epoch than districts where the glaciers have reached a great size, because it is difficult to connect the enlargement of the snow region with the length of the glaciers proceeding from it. (4.) That the temperature seems to have been lowered to a greater or less extent in all parts of the earth, though whether this occurred in strict contemporaneity cannot be ascertained, and the remark possibly may not be true of equatorial regions.

Some authorities maintain that the Glacial Epoch was interrupted by one or more intervals of considerable duration when the climate became comparatively mild. In many places masses of till and boulder clay are parted, as already described, by thick and widespread beds of sand and gravel; in some the latter are associated with laminated clays, peats, and lignites. Such intercalations have been observed in Scotland,[1] and still more markedly in the neighbourhood of the Alps; for instance, at Utznach and Dürnten, on the northern side of the Lake of Zürich. At the former place the distinctly stratified deposits are nearly 100 feet thick,[2] and rest upon Miocene rock; at the latter, where the lignite alone is from 5 to 12 feet in thickness, these deposits are underlain by a stony clay, which some consider to be morainic in origin, though this is not universally admitted. At Wetzikon, however,

[1] See Professor J. Geikie's "Great Ice Age," chap. xi.

[2] The gravels associated with the lignites are probably about the same age as those described on p. 32.

near Lake Pfäffikon, in the same district, where the lignitic beds, according to Professor Heer, range from 13 to 30 feet, striated stones and erratics occur in the clay below. In all three places the overlying deposits are morainic. Somewhat similar lignites have been found in other parts of Switzerland, in Savoy, and on the south side of the Alps, as at Carignano, Lanzo, &c.[1] With these occur remains (among them bones of *Elephas antiquus*) indicative of a less severe type of climate; and the remarkable breccia at Hötting, in the valley of the Inn, contains the leaves, &c., of palms. The age, however, of this last deposit is not beyond dispute. That the glaciers were liable to important oscillations seems to be proved, but whether the evidence suffices to establish interglacial epochs, in the usual sense of the words, is more doubtful. When the snow-fields, as in the Alps, were much more extensive than they are at present, the glaciers which radiated from them would be more sensitive to minor climatal changes. Even now they oscillate considerably.[2] But during a Glacial Epoch, an inch, either more or less, of precipitation might mean a considerable advance or retreat of the ice in the lowlands. Moreover, if the changes of level during this epoch amounted, as many geologists maintain, sometimes to 1500 feet, or even more, this alone would

[1] See for others Sir H. Howorth, "The Glacial Nightmare," p. 467.

[2] Their movements seem to exhibit a certain periodicity, the duration apparently being from about thirty to forty years.

make a great difference in the size of the glaciers.[1] In Britain, where there are no high mountains, such a subsidence, as already indicated, would probably exterminate every glacier, and might make all the difference between an ice-sheet and a snow-capped group of hilly islands; but the occasional erratics, and the intercalated patches of boulder clay in the sandy beds, mentioned above, indicate (on this hypothesis) the presence of considerable masses of floating ice, so that the advocates of a submergence cannot allow of any marked improvement in the climate. Indeed, if they are right in supposing the movement downwards to have been so great, the time of maximum depression may even have corresponded with that of the most intense cold. Hence the question of the occurrence of interglacial epochs, or of prolonged interruptions to the continuity of the one great Glacial Epoch, is more dependent on that of the level of the land than might at first sight be supposed, and cannot be ascertained, so far as concerns Britain, until that question is settled, or until the relation already mentioned —that between the area of the feeding-ground and the length of a glacier—is more accurately known.

[1] A general subsidence of 2000 feet in the Alpine region, as it now exists, would raise the snow-line to the present level of 10,000 feet, and almost, if not entirely, efface the glaciers in such a region as the Graians. The peak of the Grivola, in all probability, would look down upon two or three shrunken glaciers of "the second order," like those which now nestle in the heads of the glens around the craggy summit of Mount Emilius.

CHAPTER II

POSSIBLE CAUSES OF A GLACIAL EPOCH

ASSUMING a low temperature to have prevailed generally in the Northern Hemisphere during the Glacial Epoch, as has been described in preceding chapters, and the like to have happened, though not of necessity at precisely the same time, in the Southern Hemisphere, what explanation can be given of these changes of climate? Some have suggested that the solar system in its journey through space traverses regions of varying temperature. These, however, have only a hypothetical existence, so that we may pass on to explanations which appear more worthy of serious consideration. Of them one group seeks the cause on the earth itself, the other in its position relative to the sun.

As regards the first, a glance at a chart representing the annual isotherms shows that they depart widely from the parallels of latitude, especially in the temperate and circumpolar regions of the Northern Hemisphere. The line of 32° F.[1] in Central North

[1] Here, as elsewhere, unless it is expressly stated, the annual isotherm is to be understood.

America for some distance west of Hudson Bay nearly corresponds with the 50th parallel. Both in Alaska and in the opposite direction it gradually mounts into higher latitudes, till it gets beyond the 70th parallel, rather to the west of the North Cape of Norway. Thence it slopes downward to Archangel; then to Tobolsk (58° 21′); and finally descends in Eastern Siberia rather below the latitude of London. Thus places 20° of latitude apart may have the same temperature, and those on the same parallel may differ by nearly 20° F. These variations in the course of the isotherm depend upon the physical geography of the globe, upon the distribution of land and water, and upon the elevation of the place above the sea-level. The last factor, however, is probably in most cases of secondary value in dealing with extensive regions. As a rise of 300 feet roughly corresponds with a fall of 1° F. in the temperature, the reduction necessary for bringing about a Glacial Epoch would require an elevation of 6000 feet in the case of England, and not much less for the Alps. But any such elevation is most improbable in either region, and many geologists even maintain that the former, during a part of the Glacial Epoch, stood at a lower level than at present. This, however, is not the only difficulty. A heavy snowfall or large glaciers means considerable precipitation. Though the cold is so great both in Eastern Siberia and near Hudson Bay that the ground is permanently frozen in the latitude of our

eastern counties, yet there are neither ice-sheets nor even glaciers, because the climate is comparatively dry. Hence no hypothesis in explanation of the Glacial Epoch is admissible if it involves any very serious alteration in the distribution of sea and land.

At the present time North-Western Europe is abnormally warm. The temperatures of Tierra del Fuego, of South Georgia, of the Straits of Magellan, all in the Southern Hemisphere, are seven or eight degrees lower than those of corresponding places in Britain; and the temperature of London is often 10°, and occasionally at least 18°, above that of places on the same parallel of latitude. The proximity of the Atlantic is an important factor in producing this abnormality; in the opinion of many competent judges it is mainly due to the action of the Gulf Stream. This is supposed to make a difference of 7.5° in the temperature of North Wales, and still more in that of Scotland and of Norway. To put an end to the Gulf Stream would not require any very extraordinary geographical changes, and this might be done without very seriously diminishing the amount of precipitation on the western coasts of Europe, for the general drift of the warmer air and water would still be in the same direction as it is at present; but the reduction in temperature thus obtained would be insufficient, and a further one of at least 12° be requisite.[1] If North Wales were elevated

[1] See p. 234.

2000 feet, the increase, both in the height and in the distance from the sea-coast, might lower the temperature by about 11°; that is to say, the most favourable geographical conditions which can be imagined—of which, however, the permanence during the Glacial Epoch is very questionable—would be barely sufficient. The same may be said of the Alps and of North America, and in the case of these it is doubtful whether the physical changes would not seriously affect the amount of precipitation. In the latter region, also, the evidence in favour of a depression having occurred during part of the Glacial Epoch seems incontestable. Hence it is very doubtful whether geographical changes afford an adequate explanation. Moreover, by adopting it we are immediately confronted with a new and even more serious difficulty. The temperature of Britain at the present time is rather abnormal; it is higher than the average for its latitude; but a much warmer climate prevailed during the earlier and greater part of the Tertiary era.[1] Of such an alteration as this it is almost impossible to find an explanation in geographical changes. Hence, though they may be important, they cannot be the sole factors in bringing about modifications of climate.

[1] The temperature of Central Europe in Miocene times was probably about 16° F. higher than it is at present, and was even more (about 4° F.) during the Eocene period. The flora and fauna of the London Clay and the Bracklesham Beds indicate a climate more like that of Northern Africa than of Southern England.

We are thus driven to seek for an explanation outside the surface of the earth. Some geologists attribute these alterations in climate to changes in the form of the earth's orbit. This is an ellipse, the shape of which varies constantly, though very slowly. Sometimes it is nearly circular, but at others more elliptical than it is at present. These changes, though they do not materially affect the total amount of heat received from the sun in a year, make a considerable difference in the manner in which this amount is distributed; because the more elliptical the orbit the greater the difference in the length of the seasons of summer and winter, and in the maximum and minimum distances of the earth from the sun. As an illustration, suppose that in the Northern Hemisphere the winter occurs when the earth is in aphelion,[1] and the summer when it is in perihelion. Under these circumstances the former season is longer and colder, the latter one is shorter and hotter. In the opposite hemisphere the winter will be correspondingly shorter and milder, the summer longer and cooler. It is stated that when the earth's orbit assumes its most elliptical form the amount of heat received by a particular hemisphere in the two portions of the orbit must be in the ratio of 63 to 37, while the difference in the length of the seasons is thirty-three days. If, then, the Northern Hemisphere were in aphelion during

[1] Aphelion and perihelion mean respectively at the greatest and at the least distance from the sun.

the winter, the mean daily heat for this season would be represented by 0.68, and for the summer by 1.38. The corresponding allowance in the Southern Hemisphere would be 0.81 and 1.16. Climatal conditions in the former case would be more extreme than in

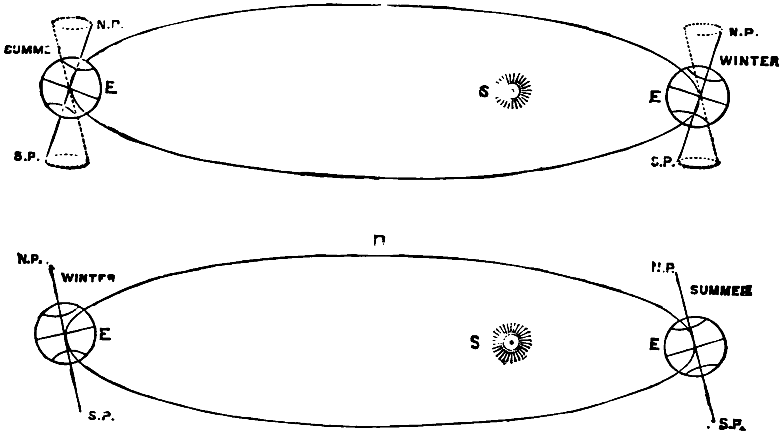


FIG. 24.—Diagram showing effect of precession: *A*, condition of things now; *B*, as it will be 10,500 years hence. The eccentricity is, of course, greatly exaggerated.

the latter, and, if other things remained equal, the accumulation of snow and ice in the one would be greater than in the other.[1]

But there is another astronomical fact to be considered which may produce modifications of climate.

[1] See Sir R. S. Ball, "The Cause of an Ice Age," chap. v., where the argument is worked out in detail.

While the form of the orbit is slowly changing, the position of the earth's axis of rotation is altering more rapidly. It does not remain exactly parallel to itself while the earth travels round the sun, but undergoes a slight displacement.[1] This precessional movement, as it is called, in combination with an actual revolving motion of the orbit itself, reverses at certain intervals the conditions in the two hemispheres.[2] If for one of them, at any time, mid-winter occurs when the earth is in aphelion, then at the end of 10,500 years this season will fall in perihelion. Thus in each hemisphere the severity of a Glacial Epoch, produced by a high eccentricity,[3] would be alternately intensified and mitigated. This, it is urged, would account for the apparent fluctuations in the magnitude of ice-sheets, to which reference has been already made. At first sight this explanation seems quite satisfactory; it fails, however, to find favour with some very competent judges, who, while admitting the mathematical facts, doubt whether any marked effects would be produced on climate.

[1] An explanation of the nature and the cause of this and other movements will be found in any text-book of astronomy. If a line drawn through the sun were to move so as to keep always parallel to the earth's axis, the former would describe a cone in the course of about 25,800 years.

[2] The reversion would take place from precessional movement alone, but the cycle of change is shortened by the movement of the orbit itself. In the one case the cycle would be about 25,800 years, in the other it is about 21,000.

[3] The eccentricity is a fraction indicating the departure of the orbit from a circular form.

It would be difficult to give a full statement of their arguments in these pages, because the discussion of so many details would be necessary; but it may be possible to convey, in a few words, some idea of one of the latest and most formidable difficulties with which the apparently corroborative argument advanced by Sir R. S. Ball has been confronted. Doubts have been often felt by those who considered this question, whether the method he had adopted in estimating the mean daily amount of heat received by a hemisphere in the two parts of the year (summer and winter) was not somewhat misleading when it was applied to the climate. Sir R. S. Ball, in the work already quoted, represents the average daily receipt of heat in the Northern Hemisphere under the present, the most genial, and the most glacial conditions, in the following tabular form:—

Present conditions:—	
Mean daily sun-heat in summer (186 days) . .	1.24
Mean daily sun-heat in winter (179 days) . .	0.75
Genial conditions:—	
Mean daily sun-heat in summer (199 days) . .	1.16
Mean daily sun-heat in winter (166 days) . .	0.81
Glacial conditions:—	
Mean daily sun-heat in summer (166 days) . .	1.38
Mean daily sun-heat in winter (199 days) . .	0.68

To point the moral, he compares these conditions with that of a man who receives a salary of £100

a year in daily payments variable in amount. This salary, to begin with, is divided into two portions of £63 and £37, corresponding with the total amounts of heat received during the summer and the winter seasons, whatever be their relative length. Under the genial conditions, with a summer of 199 days and a winter of 166 days, the daily income in the one period is 6s. 4d., in the other it is 4s. 5½d.—a marked, but not a very discouraging, difference. But when the summer consists of 166 days, and the winter of 199 days, the daily income is 7s. 7d. in the one case, and only 3s. 8½d. in the other; or "a short and merry life" is followed by a long period of privation.

Doubts, as we have said, were felt whether the facts of the case could be presented with sufficient accuracy by such a simile, for a nearer parallel to climatal conditions would be found by taking the payment at the equinoxes, which should be $\frac{£100}{365}$, or 5s. 5¾d., and supposing the daily income to vary from it as a standard.

During the summer season the man's income would rise by small daily increments to a maximum, and then decline again; during the winter it would fall in like way to a minimum, and then recover. Thus there would be two rather short epochs in which the ease of affluence and the pinch of poverty were very sensible, with intermediate longer epochs in which neither was remarkable. In such a case the "bad times" take

the form of a short sharp pinch, like a hard frost in England, rather than of a long season of poor living. Fairly healthy people would find the former a less serious trial than the latter; and this appears to hold good, as we might anticipate, in regard to climate. The question, however, has been recently submitted to the direct test of mathematical methods. Mr. E. P. Culverwell[1] has calculated the effect which these different diurnal increments and decrements would produce on the climate of a locality, and has discovered it to be much less than when they are estimated by Sir R. S. Ball's method. For instance, the difference between the climate of London at the present time, and under the Glacial conditions (other things remaining unchanged), would be rather less than would be produced by an addition of 4° to the latitude of the metropolis. In other words, the effect would be to transfer the climate of the Firth of Forth to the valley of the Thames.

But the astronomical explanation of the cause of a Glacial Epoch also suggests some indirect difficulties which seem to be rather serious. The variations in the eccentricity of the earth's orbit can be ascertained for a long period of past time. Dr. Croll[1] has calculated them at intervals of 50,000 years apart for the last 3,000,000 years, and has represented the

[1] His paper, read at the meeting of the British Association at Oxford, appeared in the *Geological Magazine* (1895, pp. 3, 55), while this book was in the press. See also *Philosophical Magazine* (1894), p. 541.

[2] "Climate and Time," chap. xix.

results graphically by a curve. According to this, an era of high eccentricity commenced about 350,000 years, and came to an end rather more than 50,000 years before the year 1800 A.D. During this era the eccentricity thrice became very high, its value being reduced in the intervals, though it was still considerable. Thus the conclusion of the Glacial Epoch should be fixed at not less than 50,000 years ago. But attempts have been also made to approximate to this date by other and less direct processes, and they generally indicate a more recent ending, varying from about 10,000 years (probably too small) to 30,000 years ago.

This, however, is not all. The Tertiary era was one when, as already stated, the climate of Europe, if any truth can be placed in fossil evidence, was generally warmer than it is at present, and during part of the Eocene period it was almost tropical. But for nearly the whole of the 3,000,000 years covered by Dr. Croll's calculation (which limit one would suppose would approach, if it did not fall within, the margin of the Eocene period), the eccentricity rarely sinks below its present value, and for a very great part of the record is much above it. From this we should infer that a low temperature must have prevailed, with little interruption, for some 3,000,000 years prior to B.C. 51,800, and have been accentuated by at least five very definite Glacial Epochs, or rather connected groups of such epochs.

This result accordingly appears to compel us either to assign the whole of this period (almost 3,000,000 years) to the Glacial Epoch of which we have been speaking,[1] or to admit that changes in the eccentricity of the earth's orbit do not produce very important effects on climate.

Some geologists have supposed that the earth's axis of rotation is subject, in the course of time, to important changes in position. It is true that the obliquity of the ecliptic,[2] that is, the angle between the plane of the equator and the plane of the orbit, is slowly altered. The amount, however, is comparatively small, for it is only 1° 22′ on either side of 23° 28′, the value of the obliquity in 1801. This at most would augment the Arctic, Antarctic, and each Tropical region by rather less than a degree and a half, and would diminish the Temperate zones by twice that amount; or it would correspondingly diminish the former and augment the latter. This no doubt would produce some effect on climate, but not such as a Glacial Epoch demands. But by some geologists a more radical change has been advocated. They have supposed that alterations in the shape of the globe, such as elevations and depressions of the

[1] This would require us to demand that the time covered by the geological history of the earth should be enormously long.

[2] No account is taken of the slight change due to the nutation of the axis, because its amount is very small, and if it produced any appreciable effect, this should have been discovered by now, as its period is only nineteen years.

crust, new groupings of sea and land, &c., make it rotate about a fresh axis, and thus change the geographical position of the poles. But in the opinion of mathematicians who have studied the subject, the mass of the equatorial protuberance[1] is so large, that this, as it were, steadies the globe, and any change which may be regarded as probable, or even possible, would not suffice to alter the position of the axis of rotation by so much as 5°. But even if mathematicians permitted an appeal to this hypothesis, palæontologists would forbid it, for they affirm that throughout all Tertiary times, and probably through Secondary also, there has been a zonal distribution of life in the Northern Hemisphere similar to that which now exists.

Other geologists, despairing of finding an adequate explanation in either the earth's geography or its position in its orbit, have suggested that the heat emitted by the sun is irregular in quantity. Variable stars undoubtedly exist, but we have no means of knowing whether the sun be one of these. Moreover, an epoch of declining temperature would hardly be succeeded by one of greater incandescence without some cause for the latter, and it is difficult to discover one which would not produce in the solar system catastrophic changes more marked and extensive than any to which our earth bears testimony.

[1] That is to say, the mass due to the amount by which the equatorial radius exceeds the polar radius, viz., about 13½ miles.

It follows, from what has been said above, that the low temperature which undoubtedly prevailed during the Glacial Epoch has not yet received any satisfactory explanation. Each one that has been proposed is either inadequate or attended by grave difficulties. It is therefore probable that some factor which is essential for the complete solution of the problem is as yet undiscovered, or, at any rate, the importance of one which is already known has not been duly recognised.

CHAPTER III

THE NUMBER OF GLACIAL EPOCHS

IF the Glacial Epoch was the result of cosmical causes, more or less periodic in character, or even of geographical conditions not very abnormal, it ought to have recurred several times in the past history of the globe. How far can tills, boulder clays, or other traces of such epochs be found? In Tennessee and North Carolina certain conglomerates overlie the Laurentian masses; in the North-West Highlands of Scotland similar deposits rest upon very ancient coarse gneissoid rocks, the surfaces of which often are more or less rounded. These have been cited as indicative of an ice age at the very outset of, if not earlier than, the Palæozoic era, but it is generally admitted that the claim cannot be substantiated. There are breccias in the Devonian rocks of the Lammermuir Hills, but even Professor J. Geikie doubts whether these can be regarded as evidence of ice action; and thick conglomerates occur at the base of the Carboniferous system in the North-West of England, the pebbles of which are sometimes striated. This, however, is now generally admitted

to be the result of subsequent earth movements, and the mass itself suggests the action of water rather than of ice. In Victoria (Australia) deposits assigned to the Devonian system contain boulders, and in one case (on the Lerderberg river) even grooved stones. Angular fragments of granite, quartz, &c., occur rather plentifully in the Carboniferous limestone near Dublin, but these seldom, if ever, exceed eight inches in diameter, and most probably have been transported by large seaweeds. In the coal-seams both of England and of America boulders are sometimes found, which commonly are pretty well rounded. They are not very rare in the Lancashire coal-field, where the majority are a hard grit or quartzite, and the largest specimens weigh over 200 pounds.[1] Generally, they are more or less embedded in the actual coal-seams, and are not associated with any perceptible amount of sand or gravel. This puts ordinary torrential action out of the question, so the instrument of transport may have been either the roots of a tree or a piece of shore-ice during a slight flood.[2] But even if it were the latter, this of itself would be insufficient to establish the existence of a Glacial Epoch. Moreover, though the vegetation

[1] One or two have been found in the South Staffordshire coalfield. M. Stirrup, *Brit. Assoc. Report*, 1887, p. 686.

[2] Professor Boyd Dawkins informs me that he has often seen stranded on the sands near Holywell (Flintshire) pieces of ice into which boulders were frozen, sometimes bigger than a man's head. These had been transported by floating down the swollen stream from the upper waters of the Dee above Ruabon.

of the Carboniferous period does not, of necessity, indicate a high temperature, it is hardly such a one as would be likely to endure very severe cold.

The Permian deposits in North-Western and Central England contain breccias, which occasionally, as in the Isle of Man, attain to considerable thicknesses. The same occur in the Midlands, for instance, in the Clent Hills, overlooking the Severn Valley. They consist of angular and subangular fragments (sometimes over two feet in diameter) representing various igneous and older Palæozoic rocks. The late Sir A. Ramsay believed them to have come from the Welsh and Shropshire uplands—or, in other words, from distances of between twenty and forty miles—and some of them exhibit markings which he regarded as glacial striations. Professor Lapworth, however, thinks that the materials have been derived from ridges in the immediate vicinity which are now concealed. There is much to be said on both sides of this question, but, as regards the striations, I am convinced, after careful study of the specimens in the Museum of the Geological Survey, that they are due to earth movements and not to glacial action. Similar breccias, though on a much smaller scale, occur in Leicestershire. Here also the fragments comprise so many varieties of rock as to make it hardly possible that all can have come from the immediate neighbourhood, and yet they are generally subangular and angular, as if they had escaped being

worn on their journey.[1] Some of these exhibit striæ which more closely resemble those produced by ice. Huge masses of breccia also exist in the Rothliegende (or Lower Permian) of Germany, which have been regarded by some geologists as due to the action of ice; and in South Africa Mr. G. W. Stow has described boulder beds which are morainic in aspect and contain striated fragments. They rest upon underlying rocks well rounded and mammillated, "which are covered by deeply incised glacier grooves, pointing in a direction which at length leads the observer to the pre-Permian mountains, whence the stones were derived which formed these ancient moraines." A clay containing boulders, often several tons in weight, also occurs in Natal, and is considered to be Permo-Carboniferous in age.[2] Somewhat similar boulder deposits occur in the Ecca beds at the base of the Karoo formation (the latter being probably Triassic in age). In India the Talchir group (Carboniferous) contains numerous boulders—sometimes six feet in diameter—embedded in a clayey material. These are curiously facetted and striated, and the underlying Vindhyan beds are similarly marked. Boulder beds also have been discovered at more than one locality in Australia, which are probably Permian or Carboniferous.[3]

[1] *Midland Naturalist*, February and March 1892.

[2] *Quart. Jour. Geol. Soc.*, xxvi. (1870), p. 514; xxvii. (1871), p. 534.

[3] A valuable summary of the evidence as to many of these Indian,

In the Upper Oolite of the east of Sutherland are singular breccias; they alternate with laminated strata containing plant remains and marine shells. The fragments, which are generally angular or subangular, may be of any size up to several cubic yards, and nearly all are from the Old Red Sandstone. They are piled together pell-mell, and somewhat resemble morainic deposits. Professor Judd, however, whose description we have abridged,[1] thinks that they have been more probably transported to their present site by floods, and are thus the indirect rather than the direct result of ice action. Boulders, which occasionally may be over a cubic foot in volume, but commonly are less, occur not infrequently in the Cambridge Greensand, and similar though smaller stones have been found in the "Red Chalk" of Hunstanton. These represent several varieties of rock, for which, on the whole, a northern origin seems probable. In the Chalk itself a boulder of a kind of granite[2] was found in a pit near Purley, associated with sea-sand, shingle, and smaller water-worn boulders. Also in a tunnel of the London,

African, and Australian deposits is given by Dr. W. T. Blanford, who thinks that they are all approximately contemporaneous, and fall within either the latter part of the Carboniferous or earlier part of the Permian period. *Quart. Jour. Geol. Soc.*, xlii. (1886), p. 249. Those in the Punjab are described by Mr. A. B. Wynne, *ibid.*, p. 341.

[1] *Quart. Jour. Geol. Soc.*, xxix. (1873), p. 97.

[2] The size is not known, for it was broken up by the workmen, but a fragment weighed about twenty-four pounds. Lyell, "Principles of Geology," chap. xi.

Chatham, and Dover Railway, near Lydden Hill, a mass of coal or lignite about four feet square and four to ten inches thick was embedded in the same formation. These, especially the former, probably indicate the presence of floating ice. Also in the Olive group of the Salt Range in India, referred to the higher part of the Cretaceous system,[1] is a boulder-bed resembling that in the Talchir group.

The Tertiary strata of Britain do not show the slightest signs of glacial action till the time when the era ended in an age of ice. But the Alps present us with some puzzling deposits. This chain is formed of a mass of sedimentary and crystalline rocks folded together. Among the most recent of the former is a group of deposits called the Flysch, which occurs on both sides of the chain, though it is more conspicuous on the northern, where it extends practically along the whole length from east to west. It is not always quite of the same geological age, beginning earlier in the former direction and lasting longer in the latter, but in the Oberland district it is nearly contemporaneous with the Middle and Upper Eocene of Britain. Certain beds in the Flysch contain huge erratics. These, in one of the most noted localities, the Habkerenthal, not seldom range between twenty and forty cubic yards in volume.[2] Five or six

[1] Or possibly a little later. *Geol. Mag.*, 1886, pp. 492–495. But some regard the deposit as late Palæozoic in age. Here boulders, sometimes striated, occur in a fine silt.

[2] Sir C. Lyell, "Principles of Geology," chap. x., who describes

varieties of granite may be found among them, most of which are not known to occur *in situ* anywhere in the Alps. The rock in which the erratics are embedded is a coarse shale or imperfect slate of a dark colour, in which are beds of a breccia more or less subangular or of a conglomerate; these often occurring in comparatively small lenticular patches, as if a load of stones had been suddenly shot down on to the muddy bed of the sea. In another locality a short distance above Sepey, on the road to Ormond-Dessus, grits, conglomerates, and breccias are interbedded with either a similar slaty rock or a dark muddy limestone. Here the more coarsely fragmental layers occasionally reach a considerable thickness, and are full of boulders, which range from two or three cubic feet in volume to nearly the size mentioned above, and a huge block now and then appears to be isolated in the mudstone. At this locality also very different kinds of rock are represented in the boulders—various sediments, schists, gneisses, and granites—the last generally attaining the largest size. Here, however, the rock commonly resembles one of the Alpine granites. Evidently these beds of fragments are not moraines; at the same time it is difficult to understand how such huge masses as have been mentioned could be transported without the aid of ice. But the tempera-

this and other localities, states that one block was 105 feet long, 90 feet wide, and 45 feet high. This, however, I believe to be an exceptional magnitude.

ture in this geological period, if any trust can be placed in palæontological evidence, was much higher than it is at present, and the contemporaneous systems in England and France, where fossils are generally more abundant than in the Alpine region, give no sign of any interruption. Swollen torrents, descending as "mud avalanches" from rather lofty mountains, might produce such deposits; but the Alps, as yet, had not been upreared, and the existence of a range immediately to the north of them, which some have assumed, is not only unsupported by any direct evidence, but also is in itself very far from probable. Such a range, if it furnished these masses, must have been an important physical feature quite late in Eocene times, and its complete disappearance is unaccountable.

Somewhat similar deposits occur in beds of Miocene age in the Superga and other hills near Turin.[1] These must have been some distance from the mountains, and the temperature at this time also seems to have been distinctly higher than at present. The Alps, however, then existed as a mountain chain in the region which they still occupy. As the evidence stands, we can neither affirm nor deny the possibility of the occurrence of glacial epochs in the Eocene and the Miocene period, for by adopting either position we are entangled in most serious difficulties; the existence during these periods of a general low

[1] Also described by Sir C. Lyell, *op. cit.*, chap. x.

temperature or of high mountains in these localities appearing to be almost impossible in the former period, and not very probable in the latter one.[1]

To conclude: The testimony of the rocks not very seldom suggests the presence of floating ice. This, however, even now is not rare at certain seasons in the Atlantic almost as low down as latitude 40° on either side of the equator, and thus by itself affords no proof of a Glacial Epoch. Only once before Pleistocene times does the testimony seem favourable to the prevalence of a rather low temperature over a large area of the globe; that is, late in the Carboniferous or early in the Permian period. So far, then, as the evidence at present goes, a Glacial Epoch appears to have been a very rare, perhaps an almost unique, episode in the history of the earth.

[1] It must be remembered that the foot of the Alpine chain is more than ten miles away from the Superga, at the nearest point; so that, even if the Miocene peaks were more lofty than those which exist at the present time, this alone seems hardly enough to account for the transport of the blocks.

CHAPTER IV

GLACIAL DEPOSITS AND GENERAL PRINCIPLES OF INTERPRETATION

EVAPORATION must precede precipitation. This is a truism, but it may be forgotten. What descends as rain or snow must be first pumped up from the sea by solar heat. Hence alterations in the magnitude and distribution of the oceanic areas will cause some variation in the rainfall of the globe. These, however, in late geological times are not likely to have been large enough to affect seriously the total precipitation, though they may have materially influenced that of particular regions. But if the Glacial Epoch resulted from a diminution of the sun's heat, and a consequent general lowering of temperature all over the globe, evaporation and precipitation would be alike affected. In such case, assuming the Gulf Stream to follow its present course, the rainfall (or snowfall) on the British and Scandinavian coasts would be less than it is at present, not only because a smaller amount of water would be gathered from regions farther south, but also because the generally lower temperature would be likely to deprive the air

of a larger part of its burden before it reached the north-western margin of Europe.

If, however, the Glacial Epoch were due to causes which affected one hemisphere only (as the northern), then, though the total rainfall of the globe might not be altered, its distribution might be varied. But in this case, we can hardly conceive that glacial conditions could have existed in Europe so far south as latitude 50° unless the Gulf Stream were diverted; and if this happened, not only would it seriously diminish the water supply to the more Western and Northern regions, but also there would be a greater drain on that supply in course of transit. Hence, in endeavouring to depict the state of such regions in glacial times, we must not speculate on the results of accumulation, supposing that the vapour at present precipitated were received in a solid form, but must compare them with the present condition of other regions on the earth's surface which are considerably more distant from the equator. Thus the vast polar ice-caps of glacial ages, imagined by some geologists, seem hardly better than "the baseless fabric of a dream," for they would require conditions mutually antagonistic, that is to say, a large precipitation and a much lowered temperature.

The existence, however, of large ice-sheets, radiating from elevated local centres, is an hypothesis which presents fewer difficulties, though even here it is necessary to advance cautiously in the reconstruction

of such ice-sheets. Accumulation is dependent for its amount on income as well as on expenditure, so that we must be careful not to assume that a store is hoarded which is out of all proportion to the annual receipts. Thus the condition of Arctic and Antarctic regions at the present day ought to furnish a very fair clue to that of the northern half of Europe in glacial times.

These regions, at any rate, seem to prove that the sea, even when the temperature is low and the snowfall fairly heavy, is very destructive to an ice-sheet or a glacier, and prevents it from advancing far from the shore. In the greater part of Greenland, even the larger glaciers are arrested in the fiords before they reach the coast-line, while in Antarctic regions, with a heavier snowfall, they do not encroach for any great distance on the sea-bed. No precise statement of this distance is possible, and much variation, owing to local circumstances, is more than probable, but we may venture on the following attempt at a rough approximation. Suppose that the ice-sheet at present ends in 200-fathom water; then, if the slope of the sea-bed be 3°—about 1 in 20—the margin of the ice would be nearly 4½ miles from land; if, however, the slope were 1 in 200, the distance would be about 45 miles. In the majority of cases it probably lies between these extremes.

Ice, however, seems to travel for much greater distances overland. The ancient glaciers of the

Alps trespassed a little on the plains of Piedmont; the glacier of the Rhone at its greatest extension apparently succeeded in reaching almost as far as Lyons. If, then, the glaciers of Britain or of Scandinavia coalesced into an ice-sheet which advanced far from the mountain region, it is necessary to begin by assuming an elevation of at least a few hundred feet in the one country and considerably more in the other.[1] The ancient Rhone glacier is supposed to have covered formerly an area of nearly 5900 square miles, and to have extended beyond the last margin of the mountain region for a distance of at

[1] Glaciers must increase in length as the mean annual temperature falls, provided the amount of precipitation remain unchanged, because the area is enlarged on which water descends in a solid form. Of this increase a very rough estimate may be obtained by supposing a mountain to be represented by a right cone. The area of its surface, or of any section contained between the positions of the generating line, will vary as the square of this line, or as the square of the vertical height of the cone, so long as its apical angle is constant. If, then, the latter line be subdivided into equal parts, the areas of the corresponding sections vary as the squares of the numbers expressing, in terms of the first one as unit, the vertical distance of the base of the sector from the summit. Suppose then we regard a mountain as a cone, and the supply basin of a glacier as a sector of it; then, as the glacier has to remove the frozen material, its length should vary with the area of its supply basin. If we apply this method of estimating to a mountain 11,000 feet high, and represent by A the area covered when the snow-line is at 10,000 feet, it becomes 4 A when this is at 9000 feet, and 9 A when at 8000 feet, as at present in the Alps. At 6000 feet it would be 25 A, and at 4000 feet 49 A. So the length of the glaciers in the valley would be $\frac{25}{9}$ths and $\frac{49}{9}$ths respectively of their present length. That is, supposing a glacier in the Alps now comes nine miles beyond the snow-line (an extreme case), it would reach twenty-five miles in the one case and forty-nine miles in the other. Obviously this method of estimating is very imperfect, and falls much short of the truth in the case of a chain

least twenty miles, the total length being no less than 245 miles.[1] But even in the south of Greenland the ice, though there is a fair amount of gathering-ground and of precipitation, appears not to travel very far over the lowlands. Hence the facts in our possession justify us in regarding with some suspicion any hypothesis which postulates an overland journey of some hundreds of miles for an ice-sheet which has had its origin not on a mountain chain, but on a region of only moderate-sized hills. In order that such a thing could happen, as seems to have been the case in North America, the conditions must have been rather exceptional.

Ice appears to be a plastic solid, changing shape very slowly in obedience to gravitation and its effects. Thus the thickness of a glacier increases in passing

like the Alps, because the principal valleys drain not one mountain only, but an extensive mountainous region. There will be, however, a set-off; for, as already said, the actual glacier-generating region does not begin till about 1000 feet above the snow-line. This, however, does not affect the proportion of the numbers; it only requires us to read "limit of glacier production" instead of "snow-line."

[1] According to Professor J. Geikie, "Great Ice Age," chap. xxxiii., the fall in the valley bed and in the surface of the old glacier was as follows :—

	Fall in Valley Bed per Mile. Feet.	Fall in Surface. Feet.
For the first 9 miles . . .	700	300
,, next 39 ,, . . .	59	$75\frac{2}{3}$
,, ,, 30 ,, . . .	$17\frac{7}{12}$	$1\frac{10}{12}$
,, ,, 100 ,, . . .	$7\frac{1}{4}$	29

The fall in the surface over the lowland between Culoz and Lyons is estimated as $42\frac{5}{12}$ feet per mile.

through a narrow part of the valley; it diminishes rather rapidly if the latter suddenly broadens out. The glaciers from two mountain glens combine to form a trunk-stream, but their constituents are mingled with extreme slowness. The two masses, as may be ascertained by a study of the morainic material, for long move side by side in practical independence, and their individuality is lost only at the edges. In all probability the morainic material is even less scattered on a very large glacier system than it is on a small one, for ice-falls and other disturbances are more likely to diversify the course of the latter, and these tend to introduce irregularities into the path of erratics. We may dismiss, as physically impossible in such a substance as ice, the idea of cross-currents, swirls, eddies, or any such movements, common though they are in a stream of water. It is, however, conceivable that, in certain exceptional circumstances, the upper portion of an ice-sheet might be moving in a direction different from that of the lower, though the latter, of course, would produce an effect on the former. For instance, suppose glaciers to form in a mountain range at the base of which an ice-sheet is passing. It might be possible, under certain special circumstances, for one of these glaciers, instead of becoming united with the larger mass, to flow down upon the surface of the latter and to continue moving in the direction of its own valley. The one mass, however, could not

glide over the other without any deviation; friction would come into play, and the upper mass would be carried on by the lower one, so that both it and its tributary materials would be gradually diverted in the direction of the main current.

Various ingenious hypotheses as to the nature of the movements in ice-sheets have been devised to account for the apparent crossing of streams of erratics and for other anomalies in the distribution of boulders, but of these it may be not unfairly said that they either are physical impossibilities, or would occur only under such exceptional circumstances that the greatest caution must be exercised in appealing to them: they may be used to account for a single anomaly, but not as general explanations.

With these preliminary remarks, we may endeavour to apply the knowledge obtained from a study of the Alps and Greenland to determining the physical geography of Britain during the Glacial Epoch. That its hill regions have been occupied, in some cases almost buried, by glaciers, that it retains in many districts indications of the action of ice, all are agreed, but the form which this ice assumed is the question in dispute. The evidence furnished by Greenland seems to lead to the following conclusions:—

(1.) An ice-sheet cannot advance far over a lowland, or encroach much beyond the sea-level, unless its effluent masses are concentrated into the lower part of the drainage area of a large valley; and even

then it is unable, as a rule, to project beyond the shelter of the coast-line, to which, in the case of a descent into a fiord, it rarely extends. Hence, in order to make the existence of an ice-sheet possible in the British lowlands under climatal conditions comparable with those of Greenland at the present day, it is necessary, as the first step, to abolish their insular condition, and to assume a general elevation of the submarine plateau from which they rise. For this an uplift of 600 feet would suffice, since the new Atlantic coast-line of North-Western Europe would be then from 80 to 100 miles away from the western shores of Ireland and Scotland.

(2.) In the next place, the mean annual temperature, now about 50° at the sea-level near Snowdon, must be greatly lowered. To what extent this is necessary, and by what causes it might be produced, has been already discussed; enough to say that it must be reduced by at least 18°, probably by rather more.

A study of Greenland leads to some further inferences. This country extends over about 22° of latitude, Scandinavia alone over somewhat more than 14°; or, if Scotland be included, we may reckon this glacier-producing area as covering about 16°. Scandinavia commonly is about 280 miles wide, though in the more southern part it broadens out to rather more than 400 miles, while the Scotch Highlands are not nearly so much; indeed, the whole breadth of that

country, at right angles to the watershed, from the Firth of Forth to the Ross-shire coast, is only about 140 miles. A considerable part, however, of Greenland, taking a rough estimate, is about 600 miles across from east to west. Thus the collecting ground of snow and ice in the latter country far exceeds that of the Scoto-Scandinavian area. But in Greenland we find that the lowlands, even in the extreme north, are commonly free from ice, except where they are opposite to the openings of the greater valleys. In such places, were it not for the sea, the ice-streams probably would protrude for not a few miles on to the lowlands, and occasionally might even become confluent by lateral extension; but it must be remembered that, as the volume of the ice supplied from the uplands would remain the same, an increase of breadth means a decrease in thickness, and thus practically a diminution of length, because surface melting is a most important factor in the wasting away of a glacier.

If allowance be made for the proximity of the sea, the condition of the Scoto-Scandinavian area during the Glacial Epoch might be represented by that of Greenland from Cape Farewell northwards to the neighbourhood of Upernavik, where the mean annual temperature now ranges from slightly below 34° F. in the extreme south to between 12° and 13° F. in the north. Allowance, however, must be made for one difference which is far from unimportant. The

water precipitation of the two regions is not the same. The rainfall in the Scotch Highlands is much greater, possibly quite four times as great as it is in Western Greenland. A snowfall equivalent to 70 or 80 inches of water would greatly increase in volume the glaciers of Greenland, and they might then extend, were it not for the sea, over a very large area of adjacent lowland. But in estimating this difference, it must not be forgotten that the heavy rainfall of the British and Norwegian coasts is largely due, directly or indirectly, to the Gulf Stream, and that the restoration of glacial conditions to these regions practically postulates a complete diversion of its waters. But this cannot be done without greatly reducing the rainfall of Scotland and Scandinavia. Still, as these regions are situated to the north-east of an ocean basin, they probably would be wetter under any circumstances than the corresponding part of Greenland, so that on this ground only the Scoto-Scandinavian glaciers, *ceteris paribus*, would be larger than those of that country. On the other hand, their gathering-ground is much smaller, which would have an opposite effect; so that although in all probability the ice which accumulated on the Scottish and Scandinavian uplands would be thicker than in corresponding parts of Greenland, its volume would not be so much greater as to interfere seriously with the accuracy of the comparison. At any rate, some compensation for the reduced supply in Greenland might be found

in the diminished waste, which is a consequence of the more intense cold of a more northern region; so that a fair parallel to the ancient condition of the Scoto-Scandinavian region might be afforded by the region extending from Godthaab up to latitude 80°, *i.e.*, to near the southern opening of Kennedy Channel. At the former place the mean annual temperature is 27.68°, at the latter about 3° F.[1] The loss from melting and evaporation must be very small on the uplands of this region,[2] so that here, as in other cases, economy in expenditure may make up for the reduction of income. If, then, the Scandinavian ice sheet, as some geologists suppose, once became confluent with that of Scotland and reached the East Anglian coast, not only must it have overcome the difficulties of crossing the very broad and deep channel, which, as already mentioned, guards the coast of Norway, but also it must have far exceeded in volume the outflow which at present proceeds from any part of Greenland.

The singular mixture and apparent crossing of the paths of boulders, as already stated, are less difficult to explain on the hypothesis of distribution by floating ice than on that of transport by land-ice, because, in the former case, though the drift of winds and

[1] The estimates given by Hann (*Handbuch der Klimatologie*), between latitude 78° and 81° vary from about 6° to 4° F.

[2] It will be remembered that all over the "great divide" in the summer time Dr. Nansen found the snow to be always dry and powdery.

currents would be generally in one direction, both might be varied at particular seasons. So far as concerns the distribution and thickness of the glacial deposits, there is not much to choose between either hypothesis; but on that of land-ice it is extremely difficult to explain the intercalation of perfectly stratified sands and gravels and of boulder clay, as well as the not infrequent signs of bedding in the latter. The waters of lakes held up by ice-barriers or by morainic deposits have been invoked to explain these phenomena; but these, while they may be applicable to certain cases, give rise to serious difficulties, such as the position of the necessary dams, the identification of the moraines, and the distinction of the deposits within and without the barriers. The distribution is sometimes hard to explain on the hypothesis of a submergence, but if the other one be adopted, the elevation at which glacial deposits occur presents its own, and very grave difficulties. Boulder clay rises on the plateau of Suffolk some 300 feet above the sea, and is not very much below this on parts of the "Northern Heights" of London. How great must the *vis a tergo* have been in order to drive the ice-sheet up to this elevation, especially when only a thickness of 800 feet is claimed for it on the coast of Yorkshire. Not only this, but the ice-sheet often must have moved athwart the trend of valleys, so that its base must have formed a serpentine curve, rising and falling sometimes much

more than 100 feet. What an enormous mass of névé must have been piled over Southern Scotland[1] and the Cumbrian region in order to drive the ice so far uphill as to deposit shells from the bed of the Irish Sea at Gloppa and on Moel Tryfaen. But if such masses did accumulate, how was it that North Wales also was not swathed in névé and surrounded by a protecting sheet of ice? The difference between the two regions, as has been already shown, whether in regard to structure and area, to temperature, or to rainfall, is comparatively slight; and it is difficult to understand in what way this can have been materially increased at a time comparatively so recent as the Glacial Epoch. The same remark is applicable to hypotheses which explain the apparent mixing or crossing of streams of erratics by assigning them to different ages of ice-invasion, in which there was first an advance of ice from Wales, its retreat being followed by an advance from the North into the Midlands, or *vice versâ*. There are some difficulties also in regard to the position of the erratics, for one would expect the second ice-sheet either to have cleared

[1] Some writers on glacial questions have apparently regarded the Highlands as the centre of the ice-sheet which invaded Western England; but, as we have seen, water, whether liquid or frozen, must obey the law of gravitation, so that much of the ice from these regions must have taken a westward or northward course, and only that which could come down from the Highlands towards the Clyde could have joined that from the Scottish Uplands. The difficulty in regard to the east coast and the Highlands is also considerable, though not so serious as the other.

away the débris left by its predecessor, if it be a powerful agent of erosion or abrasion, or to have deposited on the top of it another clay with a different crop of erratics. These difficulties may not be insuperable, but some of them are certainly serious, and they must be dealt with in accordance with the principles which are established by an inductive study of nature, and not by vague hypotheses as to the physical constitution or the distribution of ice-sheets.

Serious difficulties also are associated with the alternative hypothesis that floating ice was the chief agent of distribution in the lowland districts. There is the general objection that it assumes a greater mobility in the earth's crust than the majority of geologists at the present time would be willing to admit. The requisite upheaval is not in itself a difficulty, because elevations of at least 1200 feet are known to have occurred in an age approximately contemporaneous; but a movement also quite as great and in the opposite direction must be crowded into the Glacial Epoch; for the ground at the beginning of it is generally admitted to have stood rather above its present level. More special difficulties are the absence of distinct sea-marks, the rather sporadic distribution of marine organisms, the apparent admixture of molluscs from different depths, and the like; but these, as has been already stated, are mostly of a negative rather than of a positive character.

Probably, however, the final verdict in this difficult

trial in the court of Science will not be pronounced till more information has been obtained and polar regions have been more thoroughly studied, with a view of learning the effects, habits, and physical properties of large masses of ice. Still, we may perhaps say that enough has been already ascertained to enable the student to distinguish how far an hypothesis is an induction from facts, and how far it is an offspring of the imagination.

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[1] I am indebted to Miss C. A. Raisin, B.Sc., for relieving me from the labour of making this index.—T. G. B.

THE END.

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